# OCEANOGRAPHY

*Its Scope, Problems, and Economic Importance*

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BY

HENRY B. BIGELOW

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# FOREWORD

This book is part of a report submitted to the National Academy of Sciences by its Committee on Oceanography appointed in accordance with the following resolution voted on April 27, 1927: 'That the President of the Academy be requested to appoint a Committee on Oceanography from the sections of the Academy concerned to consider the share of the United States of America in a world-wide program of Oceanographic Research and report to the Academy.'

The President of the Academy, Professor A. A. Michelson, accordingly appointed Messrs. William Bowie, E. G. Conklin, B. M. Duggar, John C. Merriam, T. Wayland Vaughan, and Frank R. Lillie (Chairman) as members of the Committee. The Committee engaged as its Secretary Dr. Henry B. Bigelow, Curator of Oceanography in the Museum of Comparative Zoology at Harvard University.

The results of the study, including various conferences, journeys, and visits to institutions of oceanographic research, were gathered together by the Secretary into a report which was submitted to the Academy in November, 1929. The part of the report dealing with the Scope, Problems, and Eco-

nomic Importance of Oceanography was in a very special sense Dr. Bigelow's own contribution. On account of its general interest the Committee, with the consent of the Academy, has approved its separate publication. The book is an attempt to appraise the present condition of oceanographic research with reference to the more outstanding problems, so as to take bearings for future research It is in no sense a textbook or a compendium of oceanographic knowledge

The author of this book wishes to express his gratitude for advice and assistance in the preparation of special topics to Messrs. L. B. Becking, W. Bowie, C. F. Brooks, L. J. Collet, W. J. Crozier, R. A. Daly, Haldane Gee, L. J. Henderson, A G. Huntsman, Alfred Redfield, H. U. Sverdrup, W. H. Twenhofel, and R. de C. Ward.

FRANK R. LILLIE

*Chairman*
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## CHAPTER I

### INTRODUCTORY

OCEANOGRAPHY has been aptly defined as the study of the world below the surface of the sea: it should include the contact zone between sea and atmosphere. According to present-day acceptance it has to do with all the characteristics of the bottom and margins of the sea, of the sea water, and of the inhabitants of the latter. Thus widely combining geophysics, geochemistry, and biology, it is inclusive, as is, of course, characteristic of any 'young' science: and modern oceanography is in its youth. But in this case it is not so much immaturity that is responsible for the fact that these several subsciences are still grouped together, but rather the realization that the physics, chemistry, and biology of the sea water are not only important *per se*, but that in most of the basic problems of the sea all three of these subdivisions have a part And with every advance in our knowledge of the sea making this interdependence more and more apparent, it is not likely that we shall soon see any general abandon-

ment of this concept of oceanography as a mother science, the branches of which, though necessarily attacked by different disciplines, are intertwined too closely to be torn apart. Every oceanic biologist should, therefore, be grounded in the principles of geophysics and geochemistry; every chemical or physical oceanographer in some of the oceanic aspects of biology.

A feature equally inherent in sea science is that it is no less inclusive from the geographic standpoint, because the subjects with which it is concerned (the oceans) cover so large a part of the surface of our planet. And the vastness of the areas to be considered, whatever phase of the sea be under consideration, has (more than any other factor) determined the paths that the science of oceanography has followed in its advance from its early beginnings to its present state. Most oceanographers, too, would agree that the geographic factor has likewise been responsible for a failure to progress at a rate commensurate either with the relative importance of this field of knowledge in the general household of science, or with the amount of energy that has been devoted thereto during the past quarter-century.

In the nature of things, the oceanographer constantly meets a twofold obstacle of another sort, when he attempts to extend his investigations out from the shore-line to the high seas, no matter from

what headquarters he may work, in the necessity of studying the majority of oceanic phenomena and events *within* the sea, not merely upon it, or from its borders. Even if his investigation be of a sort that can be carried on in a laboratory on shore, the raw data must be gathered at sea. Therefore (as man is not an aquatic mammal) he must have a boat, a necessity that places him at a disadvantage as compared with the general biologist who turns to marine animals chiefly for convenience, and so can pick up many things of interest (and perhaps all that he needs in his particular work) on a stroll along tideline. If the student is to venture out more than a few miles from land, his craft must be large enough to contain living quarters and to navigate safely in all weathers, for oceanography is impossible unless some one does go out to sea, on short trips or on long. That is to say, for even one investigator, or one party, to gather information of any kind about the ocean in appreciable amount demands the labors of many, as reflected in the maintenance and operation of a seagoing craft, with crew to man her, with supplies for their subsistence; also (in these days) with fuel for her propulsion. And as any craft larger than a rowboat is an expensive means of conveyance for a small number of passengers, it follows that exploration into the economy of the high seas is essentially a costly undertaking.

The expense of extended voyages, combined with the necessity for such if large sea areas were to be studied more intensively than could be done from examination of vessels' log books, was no doubt the chief reason that systematic examination, even of the surface of the sea, was not seriously undertaken until the middle of the nineteenth century. But when, at about this period, science awoke to the whole new world for exploration that was offered by the oceans, it was soon learned that no very serious technical difficulties, apart from expense, were involved in extending investigations down into the abyss, whether it was a question of developing the contour of the sea floor, of gathering samples of the bottom, of sampling the living creatures, or of measuring the physical and chemical characteristics of the water.

It would, indeed, have been quite within the technical abilities of the Romans of Pliny's day to have plumbed the depths of the Mediterranean and to have explored its deep-water biota, though of course examination of the temperature and salinity of the sea must, in any case, have awaited the development of the sciences of physics and chemistry as we now know them.

Efficient gear was, in fact, so rapidly developed in the three years 1868–70, as soon as a serious start in that direction was made on the voyages of the

'Lightning' and of the 'Porcupine,' that when the 'Challenger' sailed two years later on the first ocean-wide exploration of the deeps (students of the history of science may well date the birth of modern oceanography from December 21, 1872, the date when she put to sea from Plymouth, England), the scientists on board were already in position efficiently to reap the rich harvest that stimulated many other subsequent expeditions in various parts of the world.

From that time forward, with every fresh venture below the surface of the sea, and with constant improvement in technical methods of operating gear of different kinds at great depths (we think especially of the introduction by Alexander Agassiz of wire rope for dredging and by Sir William Thomson of steel wire for sounding), a flood of new facts came pouring in so rapidly that more was learned about the sea and about the inhabitants of its deeps during the last thirty years of the nineteenth century than had been up till then. This was the heyday of the deep-sea exploring expedition, when one cruise after another was sent out by different maritime nations, when the broad relief of the ocean floors was mapped, when the general nature of the submarine sediments was determined, when the distribution of temperature and salinity was worked out in its essential outlines over the high seas, and

when the general characteristics of the deep-sea fauna were explored.

While this regional-descriptive era of oceanography will never definitely close so long as the science of the sea is pursued, there came a change, toward the end of the century just past, when persistence in the old discursive methods, determined by established habits of thought, no longer yielded new and wonderful discoveries at the rate that had been the order of the day when no one knew what was to be found at the bottom of the sea. Thenceforth, with increasing frequency, continued exploration along these preliminary lines yielded results more corroborative than novel. And a period of general oceanographic stagnation might then have succeeded to the preceding peak of activity (this did, in fact, happen in America), had there not arisen new schools, centering their attention on the biologic economy of the inhabitants of the ocean as related to their physical-chemical environment, on mathematical analysis of the internal dynamics of the sea water, and on the geologic bearing of submarine topography and sedimentation, rather than on areal surveys of one or another feature of the sea.

This conscious alteration of viewpoint, from the descriptive to the analytic, is one of two chief factors that gives to oceanography its present tone: the other is the growth of an economic demand that

oceanography afford practical assistance to the sea fisheries

This demand developed first in northwestern Europe, where, as it chanced, the fisheries were so rapidly expanding, and increasing in intensity through the adoption of more effective methods of fishing, that dread of depletion began to loom in the offing, just when oceanography was approaching the end of its nineteenth-century boom; i.e., just when it needed a fresh stimulus.

The immediate, practical result was a concentration of attention on limited coastwise areas (sites of important fisheries) as contrasted with the broad oceans, and the development of an international and official organization — the Conseil International pour l'Exploration de la Mer — with power to coordinate the scientific efforts of the Fisheries Bureaus of the several nations fronting on these areas in northwestern Europe.

It is an interesting speculation whether, without this enforced direction of scientific attention to the North Sea region, we should have come to appreciate, as clearly as we do today, that application to the adjacent oceans of principles established by intensive investigation of such test cases (warranted by the uniformity of the sea over wide areas) offers the most promising lines of approach to many of the broad, underlying problems of oceanography. How-

ever this may be, we can hardly doubt that the advance of oceanography on the analytic synthetic side would have continued slow and halting had not the Conseil and other coördinating institutions of more recent birth, but with similar aims, added their unifying influence to the attempts at synthetic investigation that would in any case have followed the alteration in viewpoint just mentioned. And it is certain that, today, the most rapid approaches toward an understanding of events in the sea are being made by orderly, intensive, and concerted attacks upon one or another phase, *via* definitely stated and apparently illustrative problems, rather than by haphazard accumulation of unrelated facts, gathered in the hope that somehow, sometime, these may be fitted together by some one. This is reflected in the fact that several broad-scale expeditions that have been sent out within the last few years — 'Meteor,' 'Dana,' 'Carnegie,' 'Marion' — have devoted their attention chiefly to extending to the high seas special lines of investigation the theoretical basis for which had already been developed from intensive studies falling in the general category just stated.

The foregoing remarks are introductory to the thesis that a discussion of certain of the underlying problems that seem most clearly to illustrate the general fields of research falling within the province

of the oceanographer, and that are now most to the fore, is integral in any rational exposition of the scope and present status of this inclusive branch of science. This, and no more, is attempted in the following chapters. To list all the problems that await the oceanographer will never be possible so long as science lives, for new ones will constantly unfold, as the boundaries of knowledge are rolled back.

In practice oceanography falls most conveniently into three chief divisions: (*a*) the geological; (*b*) the physical-chemical, (*c*) the biological.

To consider first the problems of the shape and composition of the basins that hold the oceans (i e, submarine geology); next, those associated with the physical character and chemical composition of the waters that fill these basins (physics and chemistry of sea water); and third, those of the nature and activities of the animals and plants that inhabit the waters (life in the sea) is therefore a rational order of presentation. Subsequent chapters discuss the fundamental unity of these different divisions, and outline certain of the direct economic benefits that may be expected to accrue from the study of oceanography.

A word is perhaps due the reader to explain our omission of any references to authorities. Citations are an essential part of any presentation of the results of investigation, or of any textbook, but this is

not necessarily true when the discussion is of things to be studied. In the present case to have mentioned authors would have necessitated a general bibliography of the subject; also roster of oceanographers, for each of the latter has by his published work helped to make this book possible. To cut this Gordian knot personal references are omitted.

# CHAPTER II

## SUBMARINE GEOLOGY

The submarine geologist is concerned with the shapes of the oceanic slopes and floors, with the materials of which the sea bottom is composed, with the changes these materials undergo in the process of deposition, and with such chemical and physical features of the sea water as affect these changes, directly or indirectly. In practice it is convenient to divide this general field into (1) Submarine Topography, (2) Sedimentation, and (3) Submarine Dynamics.

Many illustrations might be given of investigations carried out, and of advances won in these fields during the past half-century. But to attempt a comprehensive account of these matters would reach far beyond the permissible limits of this discussion. We wish, therefore, to make it clear that our present aim is limited to setting forth certain of the unsolved problems, and to suggesting lines of work that now seem promising.

### 1. Submarine Topography

Knowledge of the topography of the basins that enclose the oceans is the rational introduction to the

science of oceanography, because this is the facto that determines the extent, shapes, and depths o the oceans, which in turn largely control the whol gamut of thermal, circulatory, and biological phe nomena in the sea. Knowledge of submarin topography is equally needed by the general geolo gist, for (as often stated) all advances in the specifi field of submarine geology must be founded thereon while it is equally basic to our understanding o some of the most pressing problems of terrestria geology, as illustration of the methods and result of the earth's deformation in past ages. For ex ample, much more sounding is needed, in submarin hollows such as the Tonga, Kermadec, and Port Rico deeps, in connection with the problems of the strength of the earth's crust and the degree o stability of mountains and plateaus. Neither can we hope to understand the origin and history of the thousands of oceanic islands, or the geologic event that led to the formation of such archipelagoes a the Hawaiian or Samoan groups, until we know more about the exact depths and about the contour of their submerged slopes.

An exact knowledge of the topography of the bottom would go far toward establishing the pos sibility of great rockslides on the steeper submarine slopes, a question recently raised by puzzling rock formations in the Alps, Appalachians, and other

mountain chains. To quote from Doctor David White's statement to the United States Naval Conference on Oceanography, 1926, 'the bearing of submarine mapping and its geologic interpretation on the discovery of regions of submarine volcanoes, and areas of earthquake displacements must be obvious to all.' Fuller knowledge of the shape of the bottom should, as he has emphasized, disclose the locations where many of the great earthquakes originate; it should also disclose the centers of submarine vulcanism where islands may now be building up, or the reverse.

More detailed knowledge of the depth, especially for drowned valleys, etc., would also afford data for deducing the minor changes of position of shorelines, and for estimating the amount of material removed from the land surfaces by the various processes of erosion. In this connection we need to know how deep wave-base is, and how effective waves and currents actually are, as scouring forces.

The coral reef problem — a hardy-perennial controversy — is also as much a question of submarine geology as of biology, or more so, because of the fact that the upgrowth of these peculiar lime formations depends on a complex interaction of physical and chemical factors, in which temperature, salinity, currents, the absolute depth, risings or sinkings of the sea bottom, and possible changes of

sea level, all play a part. In considering the origin of any given reef, as well as in the general reef problem, the submarine topography of the island or of the continental slope in question is of first importance. This is no less essential as a basis for weighing the validity of the assumed shifts in sea level that are integral in the glacial-control theory of coral reef formation. The relation to the coral reef problems of submarine volcanoes is equally evident, and borings that have been made on Funa Futi, at Bermuda, and on the Great Barrier Reef have contributed data of great value for discussions of the problems of lime reefs. Pendulum measurements of gravity, for some distance out at sea, are also needed to combine with the geologic data above sea level as evidence whether the region in question be one of recent subsidence, of emergence, or stationary; i.e., as a test of the crustal stability of the coral reef regions in general, especially in the West-Tropical Pacific.

This matter of depth and of the local variations in crustal stability is of equal interest to the palæontologist, and to the zoögeographer, because of its bearing on possible former land connections which have been postulated to explain the distribution of terrestrial animals and plants as at present existing; no less to account for the continental separations by which different floral and faunal areas (once

continuous) are now isolated from one another. Changes in the depths of epicontinental seas, and in the degree to which the great oceans have been in free communication with one another in the past, equally concern the marine biologist as factors controlling the dispersal-routes of many marine organisms, and as affecting the ocean currents that transport animal and plant species.

The changes in the ocean currents that must necessarily follow any considerable alteration in the level of the sea floor, or in the shapes of the land masses, must also be taken into account by the meteorologist, because of their influence on the evolution of climates. Of interest in this connection is the question what configuration of the old northern oceans is reflected by the fact that fossil remains of animals and plants have been found in the Arctic, belonging to groups that can now live only at much lower latitudes, suggesting a milder climate in Eocene-Miocene times.

As pointed out elsewhere (page 231), while our charts of the more frequented coasts leave little to be desired from the navigator's standpoint, the various investigators who have attempted geologic interpretation of the configuration of the sea bottom, especially near land, have constantly faced the obstacle that few existing charts are wholly satisfactory from the standpoint of the geologist. Even

around the coasts of Europe only short sectors outside of the North Sea have been charted with the requisite detail: off the North American coast one limited area off California (recently surveyed through the coöperative effort of the Coast and Geodetic Survey and of the Scripps Institution) has alone been examined intensively with the needs of the submarine geologist in mind; and the situation is even more unsatisfactory for the less frequented parts of the world. Thus, to quote two specific examples, existing soundings do not allow satisfactory mapping of the shape of the bottom of the Gulf of Maine, a region not only made physiographically interesting for the glacial geologist by its submarine troughs and banks, but recently the site of much oceanographic activity. In fact, one of the main channels leading into one of its larger tributaries (Passamaquoddy Bay) has, within the past few years, been found considerably deeper than had previously been supposed. And a recent survey of the deeper parts of the Gulf of Bothnia, with echo soundings, by the Thalassographical Institute of Finland, proved that the existing contour charts were erroneous in many respects.

A multiplication of the soundings now existing in depths greater than one hundred fathoms is still more necessary if the geologist is to discover what becomes of the geologic structures as they plunge

into the sea; and it is obvious that much of our philosophy regarding mountain ranges is dependent on their submarine continuations. We might call attention especially to the inadequacy of existing soundings to show the fault scarps that are believed to exist along the northern slope of South America, or to outline the undersea contours of the Caribbean volcanic arcs and of the outer Bahamas.

The difficulty in this case is not one of inaccuracy of observation — on the contrary, the soundings taken by all the important maritime nations have long been extremely exact — but of their comparative scarcity everywhere outside the fifty-fathom contour. We must remember that while the soundings marked on an ocean chart may seem frequent enough, in reality they may be many miles apart. Furthermore, as they have been taken with the needs of navigation constantly in mind, it often happens that just those regions where the geologist needs the closest survey have been the most neglected, while the approaches to harbors, etc., that have been the most carefully sounded, may be the least interesting stretches of bottom, scientifically considered.

In the ocean basins, until very recently, we owed practically all our knowledge of the depth, away from the slopes of the continents, to the occasional deep-sea exploring expeditions, to the surveys that

have been made along routes thought suitable for submarine cables, and to scattering data from other sources. Of these three kinds of information, cable surveys alone, and a few lines recently surveyed with sonic depth-finders, have yielded data at all comparable, in closeness, with the surveys that have been made of shoal waters. As a result, our knowledge of the topography is still of a very generalized sort for the floors of all the oceans. And the contour lines laid down on the present bathymetric charts of the oceans are equally generalized; located on the assumption that submarine slopes are as a rule so gentle that if soundings are taken every couple of hundred miles or so they will probably reveal the existence of any important ridges or troughs. But recent soundings by the 'Meteor,' by the United States Navy, and by the vessel 'Carnegie' prove that this assumption is not as sound as was formerly supposed, but that important corrugations of the sea floor may well exist in any, or all, of the large blank spaces that remain to be studied.

The six thousand-odd soundings that had been taken in the different oceans in depths greater than 1000 fathoms up to 1912 gave an average of only one sounding for every 23,000 square miles for the troughs of all the oceans combined; one sounding for every 7000 square miles for the deep Atlantic basin. And while many deep soundings have since

been obtained with sonic methods, notably in the South Atlantic by the 'Meteor,' and in the North and South Pacific by United States, Danish and Japanese vessels — most recently by the 'Carnegie' and 'Dana' — their distribution still leaves very serious gaps. This is not surprising when one remembers how laborious and time-consuming a process sounding in deep water was, so long as it was necessary to do so with wire; to take a cast in 2000 fathoms, for instance, required at least an hour after the ship had been stopped: often much longer. From this it has followed that the growth of knowledge as to the shape of the sea floor has been inversely proportional to the depth of the water, and to the distance from land; the less frequented, too, any part of the sea, the more neglected.

The North Atlantic is, naturally, the best known ocean, bathymetrically: there is no reason to suppose that even such detailed examination as is now possible by echo sounding will seriously alter the existing picture of it. Even in the North Atlantic, however, we still lack detailed knowledge about certain of the most important features, the deeps north of Porto Rico, and in the Caribbean. We have recently learned that the representation on the charts of the slopes of the Grand Banks off Newfoundland is far from satisfactory; it was only in 1928 that the bottom contour of Davis Strait was

adequately explored; much detail is also to be added even near shore and on important fishing grounds: witness the fresh exploration of Georges' Bank and of the Grand Banks that the United States Coast and Geodetic Survey and the Fisheries Service of France, respectively, have found it necessary to undertake; also the recent surveys of the Gulf of Bothnia and of the Icelandic ridge. And our present ideas as to the contour of the deep Arctic basin rest on very few actual soundings.

We owe to the work of the 'Meteor,' in 1925–27, the first approximately correct picture of the longitudinal ridge, with furrows on either side, east and west, along which bottom water from the Antarctic drifts northward, that make South Atlantic topography especially interesting. And the unexpected irregularities that her sonic soundings brought to light on her several profiles of that ocean show the need of lines run much closer together there in latitude than has yet been attempted.

It is when we turn to the Pacific, however, that we most clearly appreciate the vast amount of sounding that still remains to be done, before adequate contour charts can be constructed. In this ocean it is only directly along the cable routes from California to Hawaii and to Alaska; in the general vicinity of Japan; along one profile from America to Australia; and along one from Hawaii to the East

Indies; that the topography of the floor of the open basin had been developed with any approach to completeness up to 1928. During that year the 'Carnegie' closed some of the most serious gaps with about 1100 echo soundings along several trans-oceanic profiles, in the North and South Pacific, while the 'Dana' has since run a line along the tropical belt. But between the lines that have so far been run, areas still remain, greater in extent than most European principalities, that are marked only by soundings far apart along the lines of the few earlier deep-sea expeditions; or scattered here and there. Thus a region off to the westward from Lower California, fully twice as large as the Republic of Mexico, is still to be marked by its first sounding. Another *terra incognita* extending northward from the foot of the Hawaiian slope nearly to the Aleutian chain, and southwestward toward the Japan deep — i.e., more than halfway across the Pacific (larger than the whole of the continental United States) — is crossed from east to west by only one line of soundings along which the individual measurements of depth lie hundreds of miles apart. In an area of nearly 2,000,000 square miles to the southwest of Chile only eight deep soundings had been taken up to 1928 when the 'Carnegie' reduced the size of this *terra incognita*. To the southward of the Jeffrey trough south of Australia, and right down to the Antarctic

edge, we again find only odd soundings, while other vast blanks still remain to be explored in the southern part of the Indian Ocean.

It may be of interest to note, in passing, that in 1929 the pilot charts of the United States Hydrographic Office listed no less than 127 shoals in the Atlantic, 68 in the Indian Ocean, and 221 in the Pacific Ocean, the position or the existence of which was doubtful.

Within the past few years, the perfecting of sonic sounding — i.e., by timing the echo sent back by the bottom — has made it necessary to cast the preceding paragraphs in the past tense, because many ships — commercial as well as governmental — are now equipped with the necessary apparatus, with which they can take almost continuous soundings in any depth of water while running at full speed. We may, therefore, look forward to a very rapid expansion of our knowledge of the shapes of the ocean basins along the usual trade routes, and on the tracks followed by the naval ships of different nations. In this way, and by special trips to regions not ordinarily traversed (and these cover a much larger proportion of the oceans than is commonly realized), ridges, troughs, and escarpments and other irregularities of the bottom may well be brought to light, such as have actually been revealed by the Panama–Australia profile, just mentioned, by

the 'Meteor' in the South Atlantic, and by the 'Carnegie' in the South Pacific, that will greatly modify prevailing notions as to the flatness and uniformity of the floors of the great oceans outside the slopes of the continents. Perhaps the major problem in this connection, which will serve as sufficient example here, is whether the bottom of the Pacific is systematically furrowed on a grand scale, as suggested by at least one bathymetric map, also by the work of the 'Carnegie,' and how it compares in this respect with the floors of the Atlantic, Indian, and Arctic Oceans.

## 2. Submarine Sedimentation

The study of marine sediments has three chief objects: (*a*) a knowledge of the sediments now being laid down under the sea is prerequisite for interpretation of sedimentary rocks on land; (*b*) better knowledge of the nature of the sediments, and of the rate at which they are now being laid down, will clarify our ideas as to the permanence of the ocean basins, as to the climates of the past, and as to the chemistry and physics of the sea bottom during past ages; and (*c*) it will throw light on the present cycle of matter within the sea.

From the first of these standpoints, if from no other, the study of modern marine sediments would be (as it has often been named) a geologic necessity, because the development of stratigraphy depends

upon a knowledge of the environment of deposition. And this development is made essential for a correct understanding of the sequence of events in the earth's history by the fact that sedimentary rocks which were originally laid down under water (salt or fresh) now cover some seventy-five per cent of the surface of the lands, while it is also probable that areas overlaid by igneous rocks are in many places underlaid by sedimentary. In fact, there are probably no large parts of the continental areas that were not under water at some time in the geologic past. Sedimentary rocks also contain a majority of our mineral resources. They are, in short, the most important element in the earth's outer shell as they affect man's undertakings.

Neither the study of modern sediments alone nor of their ancient prototypes now represented by the sandstones, chalks, and limestones can tell the whole story: only if the two be examined hand in hand can geologists hope to understand how the different classes of sediments, now solidified into rock, were originally accumulated; still more important, what chemical changes they have undergone since that time. And since sediments of different sorts are laid down in sequence, changing as the determining conditions change (e.g., if the sea floor rises or sinks; if the sea warms or cools; if the circulation undergoes any major alterations), study of the old sediments

should also give us the sequences of the changes that have taken place in the seas of old.

The task of the sedimentary geologist, therefore, includes not only an examination of the composition, texture, chemistry, etc., of existing sediments, but, equally, the restoration from these characters, and from the factors in the environment that compel the deposition of one kind of sediment and not another, of the conditions as to depth of water, temperature, activity of circulation, distance from land, topography of bottom, and so forth, under which the old sands and muds accumulated. For this he needs especially to know which classes of sediments are deposited only under special combinations of environmental factors, and which are either less sensitive or are limited by only a single factor; e.g., by the control that temperature has on the distribution of the organisms whose skeletons have been the source of marine oozes. The rocks derived from the first group have a limited, those from the second a much more general, distribution.

An understanding of these factors would make interpretation possible of the sedimentary rocks in terms of the physical and chemical state of the sea when they were deposited. This inevitably makes the submarine geologist trespass on the realms of the oceanic biologist and of the palæontologist, because it is on a knowledge of conditions of life of the mod-

ern representatives of the sand, ooze, and reef-building animals and plants of the past that such understanding must be based, so far as the organic sediments are concerned: the chalks, for instance, the radiolarian-bearing strata, the diatomaceous earths, and those limestones in the East Indies to which an abyssal origin is usually ascribed. Conversely, the palæontologist's best clue to the conditions as to depth, etc., under which ancient marine animals lived is the nature of the rocks (i.e., sediments) in which their remains are found.

The chemical changes that the impregnating water may have caused in the nature of the limy sediments on the floors of the oceans deserve particular attention, because we know that while the old sedimentary limestone and shale rocks were laid down under water, and under conditions comparable to those existing today, they differ greatly from the modern muds and oozes. In this connection new studies on the hardening (diagenesis) of marine sediments are urgently needed to explain the origin of the old unstratified rocks of the earth's crust.

Interpreting 'sedimentation' broadly, we may here mention the assistance that a detailed charting of the regional and bathymetric distribution of the more monotonous communities of animals and plants of skeleton-building types, now living on the sea bot-

tom (e g., coral or Halimeda reefs, mussel, or other shell beds, forests of deep-sea crinoids), would give to the geologist in his attempts to interpret the age relationships of strata that contain, in close association, fossil communities that differ equally widely in character.

Lime rocks have certainly been the most widely discussed of marine sedimentary formations, and in some cases, as with an oyster bed, or a reef of corals, or a swarm of Globigerinæ, the progress of the event by which lime is added to the sea floor may be easily observed. But great quantities of limy mud are also being laid down in tropical seas, the minute amorphous particles of which seem not to be the simple fragments of shells of defunct animals. Whether bacteria are responsible for the formation of these muds, as formerly supposed (page 181), or whether they result from chemical or mechanical precipitation quite independent of bacteria, or whether, after all, they are simply the end product of the breakdown of exposed limestones, beach sand, etc., as has recently been maintained, is still a moot question. This question, however, is of great theoretic interest, not only for its bearing on events now taking place in the sea, but in connection with the formation of oölitic limestones, and in relation to the relative importance of salt and fresh-water situations as sites for the formation of limestones, now and in the past.

The question to what extent the formation of limestones or other sedimentary rocks has taken place in the past at great depths under characteristically abyssal conditions, or is taking place there today, is still an open one. It is suggestive in this connection that the few short cores of the bottom (up to eighty centimeters or so long) that have been taken in deep water in the North and South Atlantic basins, with their poleward extensions, by the Nordske Nordhaus, German South Polar, 'Michael Sars,' and 'Meteor' expeditions, as well as by the recent 'Atlantis' cruise sent out by the Museum of Comparative Zoology, show, as a rule, rather a noticeable stratification even in the thin superficial stratum, in many cases with less and less lime from the upper surface of the ooze downward

At first thought it might seem that this decrease in the percentage of lime, as one penetrates into the sea bottom, reflects the solvent action of the entrapped water — i.e., the age of the sediment — raising the question whether solution of this sort may, in places and at certain times, actually limit the thickness to which lime deposits can accumulate on the ocean floors of today, by dissolving calcium carbonate from the deeper layers as fast as it accumulates on top. But the fact that some North Atlantic cores have been found to contain shells of Foraminifera still in good condition, though buried some

sixty centimeters deep below the upper surface of the ooze, suggests quite a different explanation for the stratification, namely, that changes in the temperature of the sea have caused corresponding changes in the kinds of sediments deposited. How does all this bear on the failure of geologists to find existing sedimentary rocks to which abyssal origin can safely be credited except in limited areas, such as those of Barbados and of the East Indies, and on the view that the accumulation of thick beds of calcareous sediments has for the most part been confined to shoal waters, or has taken place at great depths only under special circumstances? To learn whether lime sediments, once buried, remain intact, or, if they are subsequently dissolved, the rate at which this happens relative to their rate of deposition, a knowledge of the chemical composition (especially of the degree of alkalinity) and amount of the water that is trapped within the modern sediments of different sorts is as necessary as it is for an understanding of the changes that sediments undergo in their alteration into rock: also of the nature of the water that lies directly upon the sea floor.

Problems equally broad arise in connection with the siliceous deposits, for with silica constantly contributed by the rivers to the sea, and with no return loss either to the atmosphere or to the land (except in regions of elevation), it seems that the silica of the

earth is now tending to accumulate on the sea floor. The geologist is, therefore, as deeply interested as is the biologist in the factors that cause such accumulation of silica to take place most rapidly in cold water, and at great depths, as signboards to the conditions under which similar events occurred in the seas in past geologic ages. Among these siliceous deposits the radiolarian-bearing sediments demand special attention, both in relation to the depth at which they were deposited, as just mentioned, and because knowledge of the conditions under which they were laid down is vital to our understanding of the geosynclinal rocks, hence of the world's mountain chains.

The formation of phosphatic concretions and of glauconite on the sea bottom of today also needs fresh examination for its bearing on the origin of phosphatic and potash rocks: it is in the sea, too, that the key to the riddle of the source and mode of formation of dolomite is most hopefully to be sought (page 117).

In like manner, a study of the blue muds around the continental shoals and on the shelves is important because of the probability that many of the shales, laid down under the seas of old, were deposited in the same way. We think especially of the genesis of the Paleozoic black shales of vast extent, as to whose origin there are nearly as many theories

as students. The fact that the ordinary black shales, of marine origin, grade into the algal coals, oil shales, and kerosene shales naturally introduces us to the general question of organic matter in the sea bottom, which has direct geological bearing from many angles. The conditions of growth and the environmental factors controlling the deposition and the burial in the sea of the remains of the algæ that make up a large part of the long-buried carbonaceous shales are still an open question. Is the color of the ordinary black shales due to vegetable or to animal derivatives, or, if to both, in what proportion? And by what chemical alterations have these shales been derived from the ordinary black marine muds?

Modern industry gives economic import to the problem of the accumulation of the carbonaceous and bituminous substances on the sea floor, from which petroleum, natural gases, and other hydrocarbons are believed to have been derived. Geologists, generally, are agreed that petroleum and so forth are end-products of the natural distillation, under geologic processes, of organic material accumulating whether in the sea, in fresh water, or on land. It seems certain that in such alterations of marine sediments more organic material is involved than the oil of the copepods, diatoms, and so forth; similar though the latter be to petroleum in chemical composition. But it is still an open question whether

it is the vegetable matter or the animal fats that are the chief source for the geophysical and geochemical transformation in question. It is, therefore, important to learn to what extent the soft parts of animals are actually buried, and so preserved in the marine muds and oozes, and how they are transformed there by bacterial action. Cores, in particular, are needed to tell us the relative abundance of organic matter in the mud, from its upper surface downward, a question that bears on many of the chemical reactions that tend to alter the raw material sifting down in the bottom.

The problem of iron in modern marine deposits is important because of its bearing on the question, what part of the iron ores now being mined in sedimentary rocks were originally laid down with the latter, or in what part they entered subsequently, as secondary intrusions? Are deposits of this sort being laid down anywhere today? What, if anything, have bacteria to do with the segregation of iron in the sea? How does the common association of iron with manganese in modern deep-sea deposits bear on this problem? How sound are the chemical reactions that have been proposed to account for the deposition of either of these minerals, and what conclusion must we draw, as to the depths of the Paleozoic seas, from the distribution of iron, in deep and in shoal water, in the modern sediments?

In the interpretation of geologic time, the rate at which marine sediments accumulate is a matter of prime importance, regarding which present knowledge is practically *nil* Our only direct evidence as to how fast the limy deep-sea oozes are actually building up in thickness on the ocean beds, or even whether they are so building up at all, is the rapidity with which Globigerina ooze has been found to protect (i.e., to bury) submarine telegraph cables. But it is certain that the sea floor generally, over all the vast area occupied by the Globigerina oozes, is not rising at as rapid a rate (an inch in ten years, or a fathom in every 720 years) as this experience with cables would suggest if accepted at face value. How do the processes of solidification, of solution within the sediments as suggested by the stratification of lime just mentioned, and of the sinkings of the earth's crust as weight increases (compensated by uplifts elsewhere), balance the tendency toward accumulation?

We commonly think of the terrigenous detritus around the continents as accumulating faster than do any of the oceanic oozes. How, then, are we to interpret the fact that glacial pebbles have often been dredged, and *over* a wide range of depths (p. 37)? Is the depth to which these stones are buried a measure of the thickness of deposition since glacial times?

The probability that cores will throw light on the actual rate of deposition in given circumstances, if some time-marker can be established to start from, gives special importance to such work off coasts, the character of which was determined in the last glacial period. Circumscribed basins, scoured out so deeply by the ice sheet that mud is now being entrapped within them, are especially attractive subjects for time-studies of this sort. Projects are, in fact, under way for obtaining cores in bowls of this sort.

The degree of alteration undergone by the particles that make up the abyssal red clay in its different layers would also show something of the age of this material relative to other geologic processes, even if it cannot be measured in years.

Allied to this problem of rate of deposition is that of the size of the particles that are deposited in different regions and depths under different conditions of oceanic circulation, combined with the transport of sedimentary material over the sea floor, by waves and currents. This bears directly on the theoretic profile of equilibrium that has been supposed to represent the balance between submarine processes of transference and terrigenous contributions. Analysis of the depths at which coarse sediments are now accumulating, and of the rôle played in this connection by the scouring action of waves, tides, and currents as a governing factor, is especially desirable

from the geologic point of view, because the conglomerates and breccias that were formed in the old seas have their equivalent in the gravels and sands that are being deposited around the shores of the oceans today.

The failure of sediments to accumulate, even in deep water, in regions where the scouring action of currents or waves is strong (e.g., the Pourtales Plateau off Florida and the Wyville Thomson Ridge in the northeastern Atlantic) is also geologically suggestive. Can the fact that Devonian strata have been found lying direct upon Cambrian in certain places, with nothing between — long a geologic puzzle — be credited to similar local scourings in the Paleozoic sea?

On the steep slopes into the abyss special watch should be kept for rock masses that have broken away from the shelf and slipped down the slope. Modern deposits on the submarine slopes of the oceanic islands also bear on the sedimentary effects of landslides as pointed out on page 14.

The presence of glacial pebbles, even boulders, embedded in the bottom on the offshore banks, such as have been found far out from the land at various localities on both sides of the North Atlantic, where their presence cannot be credited to transport either by the ordinary agencies by which marine sediments are distributed over the sea floors, or by floating ice un-

der present conditions, emphasizes the importance of relicts of this sort as evidence of the distances to which the ice sheets of the last glacial period extended out beyond the edges of the modern continents. The information so far gathered on this point is only enough to whet our appetite for more. All this is bound up with the problem of climatic changes in the sea during past ages, already mentioned in connection with shifts in submarine topography (page 17) and in the discussion of stratification in the deep-sea oozes (page 40).

The thermal relationships of the various species of Foraminifera, shells of which have been identified at different depths below the uppermost layer of ooze, may prove highly significant as indices to changes in the temperature of the ocean, as already suggested. Similarly, the alternating strata of shell-bearing and shell-less clays on the bottom of the Norwegian seas emphasize the geologic fertility of studies in this field. The urgent need for more detailed information as to the temperature and other vital optima of the various pelagic shell-builders here unites the biologist with the geologist.

The regional and vertical distribution of marine sediments of different classes (when we learn the correct interpretation) also opens one promising avenue to the solution of the recurrent problem of the permanence of the ocean basins, on the answer

to which so much of our interpretation of the modern physiography of the earth depends. Is it, for example, safe to assume that where a basin is now floored with red clay (the most typical abyssal sediment), it has continued deep for geologic ages past, and that the presence of the teeth of sharks of species long since extinct, and earbones of whales that our dredges often bring up from red clay bottom, means that not enough sediment has sifted down, since Tertiary times, to bury them deeper than the instruments scrape? Or may this old stratum have been repeatedly covered by lime ooze and as repeatedly freed from the latter by the solvent action of the water, with successive uplifts and sinkings of the sea floor?

Improvement in the methods of obtaining cores of the sea bottom, at great depths, would offer new lines of attack here, for we have an index to the depth of water at which particular classes of sediments have been laid down in the fact that the limy oozes (as a class) accumulate only in depths less than about 2500 fathoms (shoaler still in the Pacific), while it is only at greater depths than those in which calcareous sediments accumulate that the red clay, or the radiolarian and diatom oozes, are found little contaminated by limy shells. Some cores suggestive in this respect have already been obtained. The presence of abyssal red clay overlying Globigerina

ooze has been used as an argument for a very considerable recent sinking of the sea floor in the mid-equatorial Atlantic, seven such cases having already been recorded from the 'Meteor' expedition. But stratifications of the opposite sort — i.e., with Globigerina ooze or diatom ooze overlying blue mud, such as even the short cores taken by the 'Meteor' revealed over a considerable area off West Africa, between 13° north latitude and the equator or of red clay beneath Globigerina (found by the 'Gauss') — do not necessarily point to a shift in the level of the sea floor. They may, on the contrary, give evidence of a change in the Pelagic fauna and flora of the overlying water, caused by a change in its temperature, or of a different dispersal of clastic material from the land. The layers of volcanic ash found in some of the 'Meteor' sediments also open interesting problems. Similar cores, and if possible, longer ones, are desiderata for all the deep submarine troughs, especially for those that fringe the continents, as possible clues to the ages of these depressions relative to the stability of the ocean floor as a whole, and relative to the ages of neighboring mountain chains on land. In the same way, the discovery of shoal-water shells in dredgings from considerable depths illustrates the importance of submarine evidence of that sort for its bearing on the possible existence of former land bridges.

As final examples of the importance of submarine geology in the household of geophysics, new work on the radio-activity of deep-sea sediments would add much-needed data on the origin and distribution of radio-activity in the earth, hence of its internal heat.

Hopefully to attack problems such as these mentioned in the preceding pages, geologists need a much more detailed knowledge of the distribution of different classes of modern sediments on the sea floor, as well as of their nature, than it has yet been possible to attain: this is especially true for the shelves of the continents, where all sorts of débris from the land overshadow the contributions made to the bottom by local shell-builders. In part, the wide regional variations in this zone are associated with differences in the nature of the source-rocks on land from which much of the material comes; this applied equally in the past. But regional differences in the turbulence of the water, and in the scouring action of tides and currents are also important in this connection, because they govern the degree of coarseness or fineness of the detritus that can be held in suspension, thus sorting the sand or mud regionally as it is laid down.

No shoal-water survey can be adequate, from the geological point of view, unless samples of the sediment be taken close together (many more per hundred square miles than would suffice in the abyss),

and throughout the entire depth range of the region in question; they must then be subjected to detailed analysis in the laboratory. Though this last requirement may seem self-evident, it has been met for very few shoal localities, because our present knowledge of shoal-water sediments is based chiefly on the data given on the navigational charts, which, in turn, are drawn from wholly inadequate samples or (as when the bottom is described as 'hard') simply from the failure of the sounding lead to bring back any sample at all. Geologically speaking, 'hard' or 'rocky' is a meaningless term, unless we know whether it was some rock fragment that the lead struck, perhaps brought from afar by glacial action ages ago, or solid ledge *in situ*, or unless at least a fragment of the material is obtained. To quote a specific example, the nature of the bottom as noted on the charts of the Gulf of Maine (one of the better-sounded seas), is of very little service to the geologist, and even when samples were collected and analyzed for this very purpose, from two hundred stations there, it proved that serious gaps still remained.

The obvious importance in the formation of sedimentary rocks of accumulations of calcium carbonate in shoal water has, it is true, stimulated intensive examination of several shoal areas in tropical and sub-tropical regions; of the reefs of Murray Island, Australia, for instance; of restricted localities around

Samoa; and of the Floridian and Bahaman Banks. Much attention has also been directed, of late, to possible precipitations of calcium carbonate from the sea water in the tropics, whether by bacterial or by direct chemical action (page 115). Similar studies of sedimentation in restricted areas are also in progress in more northern seas; around Great Britain, for example, in the Bay of Fundy, off the coast of California, and elsewhere. But these isolated projects must be greatly multiplied and extended out to the mud line at the edges of the continents, before we can hope even to sketch in the very complex mosaic picture presented by the processes of deposition in shoal water.

Samples of the sediments need not be taken at such close intervals to meet the geologic requirements in the deeps of the ocean basins, because (within certain ranges of depth, and at certain distances out from the submarine slopes), the deep-sea mud or ooze that superficially clothes the ocean floor is comparatively uniform. Consequently data from points scattered as widely as are most of the deep-sea soundings have usually been assumed to suffice for the intervening stretches, except where more detailed examination may reveal unexpected shoals or troughs dissecting the abyssal plain. This assumption, in general, is justified by the direct relationship that the types of deep-sea deposits bear to the depth,

to the distance from land, and to the plankton of the overlying waters. For as a rule the sediments of the ocean basins, far out from the land, are 'oceanic' in origin, consisting of the shells of pelagic plants and animals that rain down from above under the regions where the plankton is abundant, of the skeletons of bottom dwellers, or of the so-called 'red clay' that gradually accumulates from the disintegration of the pumice from volcanic eruptions, from cosmic dust, and from the precipitation of manganese and other less common minerals out of the sea water.

So much information has already been gathered from the bottom samples that have been collected by the various deep-sea expeditions, that further exploration is not likely seriously to alter our general conception of the character of the materials that floor the ocean basins, at depths greater than, say, five hundred fathoms; either as to the structural or chemical composition of the several classes of deep-sea sediments or as to their regional distribution.

Much, it is true, remains to be done in the abyss, to fill in the extensive blanks that still mar our charts, especially for the Pacific and for the Indian Ocean, while recent work shows that important modifications of present charts of Antarctic deposits are needed. But a much more pressing need is that of examining the vertical distribution of the sediments, by probing the underlying mass to a far

greater depth than has yet been possible. Here, as in so many submarine problems, we face a practical obstacle. With deposition proceeding almost everywhere in the sea (except right along the coastline, and in certain restricted localities where currents scour the bottom), there is no opportunity for a direct examination of submerged geologic sections, because no transversely dissected sedimentary layers are left exposed under the sea, or are accessible for examination if exposed. The collection of additional cores with the primitive instruments so far devised for the purpose would be of great assistance in the study of sedimentation. But while it is easy enough to gather mud in any desired amount from the uppermost stratum, in any depth of water, no method has yet been devised for obtaining vertical cores of the bottom more than about three to four meters long, nor have any corings of more than about eighty centimeters yet been obtained from deep water in the great oceans. The perfection of apparatus for taking longer cores is therefore an urgent need.

No further discussion is needed to make clear that the sedimentary geology of the sea is still in an elementary stage, even if judged as a descriptive science. Compared with soil science on shore, our knowledge of the muds of the ocean deeps corresponds in a way to that of some steppe or prairie

region, where the soil is so uniform over great areas that scattered tests will give a representative picture of the whole. But we know hardly more of the bottom in shoal regions than examination of a garden plot, here and there, would tell us of the agricultural possibilities of a land with widely diversified soil. Picture, too, how far geology would have progressed on land had there been no way of studying anything but the top soil!

### 3. Submarine Dynamic Geology

The study of dynamic and structural geology has been greatly handicapped in the past by the fact that two thirds or more of the earth's surface is put out of reach by its covering of water. While it is possible to survey the topography of the bottom and to gather samples of the sediments, these are only two of the factors involved in the problem of the cause of basins and continents, or of the existence of troughs, submarine ridges, and oceanic islands.

We still lack any means of obtaining samples of the rocks that underlie the oceanic sediments. But studies of earthquakes and of the volcanic rocks of oceanic islands suggest that the regional grouping of these may throw light on the constitution of the crustal material below the oceans. And the recent development of a means for measuring the force of gravity at sea (as geophysicists have for many years

been able to do on land) opens a wholly new field of oceanic research, for previously there had been no way of determining whether the high values of gravity that prevail on oceanic islands do or do not indicate an excess of material in the crust under the oceans as a whole. An answer to this question is prerequisite for any general conclusion as to whether the state of hydrostatic equilibrium or 'isostasy' that has been proved to be the normal condition of the emergent portion of the earth's surface is equally characteristic of the ocean beds. In other words, do these depressions represent the heavy sectors of the crust, just as the masses above sea level are compensated for by a deficiency of material (i.e., lightness of the crust) beneath the continents? This is one of the major problems of geophysics, because rational interpretation of the irregularities of the earth's surface must depend largely on determining the relative densities of the material underlying oceans of different depths, compared with lands elevated to different heights above the mean level of the earth's crust.

Gravity measurements at sea supplemented by analyses of the igneous rocks found on oceanic islands may, therefore, be expected to throw much light on the causes of ocean basins and continents, of the sinkings and risings of oceanic islands, and of volcanic activity, past or present, on the latter. Such

measurements may also be expected to show whether the processes that caused broad uplifts in the past are now working under the oceans to make uplifts that may appear above the sea in geologic ages to come.

Other questions are also involved For instance, is there any support for the theory that the ocean beds have tended to sink under their own weight with the lighter margins of the continents tending to buckle up in compensation? In areas, on the contrary, where the sea bottom is rising (if any such be found), might lightness compared to the surrounding lands be responsible? How is all this related to the weight of the sediments that accumulate on the sea floor, and this, in turn, to the new hypothesis (raising one of the insistent problems in modern science) that the blocks of the earth's crust that form the existing continents have not only moved horizontally to their present locations, but may so shift position again?

For such reasons a net of gravity measurements is needed over the oceans. A beginning has already been made in this direction by determinations carried out by the Dutch Geodetic Commission and by the United States Navy from submarines, on voyages from Europe to the East Indies *via* the Mediterranean and Suez Canal, and in the West Indian-Caribbean region, while a gravimetric marine survey of the East Indies from a Dutch submarine has

recently been completed. These observations have already opened interesting vistas, for while the flatter parts of the sea floor (along the lines so far run) have given values roughly in accord with the isostatic principle, decided differences have been found between the observed and the theoretic values of gravity over and near some of the deeper submarine troughs, near oceanic islands and close to the margins of the continental shelves. It may be premature to conclude that abnormalities of gravity of this sort, plus the fact that the grouping of submarine earthquakes is similar (the deep troughs seem, in particular, to be the seats of the strongest earthquakes), necessarily reflect a lack of stability in the parts of the earth's crust in question, for other explanations may be possible.

Solution of dynamic questions of this category calls for studies of the ocean deeps, of the regions around the oceanic islands, and of the margins of the continental shelves far more intensive than have yet been attempted. The discovery, for example, of a long arc of negative anomalies of gravity in the East Indies by the Dutch expedition mentioned above has already thrown new light on submarine foldings of the earth's crust.

# CHAPTER III

## PHYSICAL AND CHEMICAL PROBLEMS OF THE SEA WATER

SEA water, next to air and to fresh water, is the most uniform of all the substances common on this planet, in chemical and physical character. Therefore it does not offer to the physicist or to the chemist the opportunity that it does to the biologist for the solution of the basic problems that are today most alluring in his particular fields of study.

The immediate task of the ocean physicist, for example, is not so much to investigate the inherent properties of matter as to explain the existing manifestations of heat, light, and motion within the sea water itself. The problems most immediately pressing in these fields center about the responses of the water to solar radiation, to the atmospheric circulation, to the force of gravity, and to the centrifugal force that is set up by the rotation of the earth. These forces are all directly measurable, and can be stated in quantitative terms. Essentially, therefore, physical oceanography is an exact science. If we are not yet in a position to handle its manifestations in an exact way, it is more because our regional knowledge of the sea is still incomplete, and because our methods of mathematical analysis are not sufficiently

advanced, than because of failure to understand the basic physical or cosmic principles that are involved.

The studies of the chemistry of sea water that are at present in progress, like those of its physics, chiefly aim at enlarging our factual knowledge of regional variations, and our understanding of events that take place in the cycle of matter there, rather than at clarifying the nature of chemical processes as such. Thus they bear to the science of physical chemistry as a whole a relationship more subsidiary than do oceanic biology or physiology to current attempts to fathom the riddle of life. We may also remark that a line should be drawn between problems in the sea that involve analysis of the chemical reactions that actually take place there, and those which include chemistry only in so far as it is necessary to determine the amounts of one substance or another present in the solution or in the sediments that clothe the ocean bottom, as adjuncts to other problems. The first of these categories falls truly within the province of the chemist; but the chemical phase of the latter consists merely of routine analyses, and so may concern the theoretic chemist only in some secondary stage. As an example of the first category we might cite the problems of lime chemistry (page 114). Examination of variations in the nitrate content of the sea water *per se* might illustrate the second; it is promoted to the

truly chemical category when the cause and the effect of such variations in nitrate concentration come into account.

Sea water occupies the greater part of the surface of our planet. A study of its physical and chemical characters and of the circulatory movements by which it responds to external and internal forces is, therefore, an important item in our broadening view of the physics and chemistry of the earth, sufficient reason for making this a primary subject. But at the same time the temperature of the water, its chemistry, and the mechanical manifestations of oceanic circulation so obviously govern the whole economy of life in the ocean, produce geological results so important, and go so far to govern climates on land, past as well as present, that there has often been a tendency to treat physical, chemical, and especially dynamic oceanography chiefly as auxiliary to oceanic biology, to meteorology, or to geology. The fact that oceanographic work on the two sides of the Atlantic has long drawn its chief impetus from the economic pressure of fisheries problems has further tended toward a relegation of ocean physics and chemistry *per se*, to secondary positions. This, however, has seriously retarded the advance, not only of our knowledge of these aspects of the ocean, but even of the very branches that it was hoped to further; for it may be taken as axiomatic that only when any

scientific field is considered as worthy of intensive cultivation for its own sake can satisfactory advances be expected therein.

One effect of this tendency has been that studies of the physical and chemical state of the waters have rarely been the primary objects of the oceanographic undertakings of the past. This has applied, for example, to many of the deep-sea explorations, 'Blake,' 'Albatross,' 'Valdivia,' and 'Siboga,' among others. In America, where most of the older oceanographic exploration was sponsored by institutions whose chief interests lay in biology, the physical and chemical sides were even more neglected than in Europe, from the days of the 'Blake' until the renaissance of oceanography there in the first decade of the present century.

New viewpoints, developed of late, have, however, greatly stimulated interest in the problems of ocean chemistry and physics at all the centers where oceanographic research is now being actively prosecuted. Thus the principal programmes of the recent German expedition to the South Atlantic on the 'Meteor,' of the exploration of Davis Strait in 1928 by the United States Coast Guard cutter 'Marion,' and of the recent cruise of the 'Carnegie,' have been chemical, physical, and dynamic, recalling the attention devoted to the chemistry and physics of the sea water on the cruises of the 'Challenger' and of the

'Pola.' One or other or both of these phases of sea science are also primary objects for the Geophysical Institute in Bergen, for the Institut für Meereskunde in Berlin, for the Scripps Institution in California; as well as for the International Ice Patrol operating around the Grand Banks of Newfoundland; also for some of the Atlantic cruises of the fisheries services of European countries, of the Biological Board of Canada, of the United States Bureau of Fisheries, and of the Museum of Comparative Zoölogy.

At present, the attention of ocean physicists is chiefly focused on the following fields: (1) the distribution of temperature and of salinity within the sea, (2) oceanic circulation in detail, with the causes thereof, and (3) the penetration into it of the sun's rays and effects of the same. The problems most to the fore in oceanic chemistry today center around the concentration and distribution of the different solutes in the sea water, and around the reactions (organic or inorganic) by which the constancy of this remarkable solution is maintained or disturbed.

### 1. The Temperature and Salinity of the Sea Water

There is as good reason from the biologic side as from the strictly physical for studying the temperature of the sea, because this, more than any other one feature of the water, directly controls the distri-

bution of marine life, animal and plant. Because of the important rôle of temperature in governing the rates of animal and plant metabolism, touched elsewhere (page 154), the seasonal changes in the temperature of the water present special problems to the marine biologist in his studies of important events in the life cycles of animals and plants, such as their breeding periods, the duration of the periods of incubation or of larval life, rate of growth, feeding activity at different seasons, seasonal migrations, and many others. The temperature optima and the lethal limits need also to be determined at different stages in development for every species the life history of which is under examination. This question is of practical import in the case of several important food fishes, crustaceans and mollusks: the thermal knowledge that the biologist needs in such cases is, furthermore, of an extremely detailed sort.

Apart from the perfectly defensible wish to extend our knowledge of every phenomenon in the sea, the distribution of temperature engages the physical oceanographer in his studies of the movements of the different masses of water, both as affording direct evidence of such movements and because this is one of the two constants controlling the internal hydrostatic forces that tend to maintain a system of thermo-dynamic circulation within the oceans. The close relationship that exists between the tempera-

ture of the surface of the sea and that of the overlying air, introducing the whole broad question of the control of land climates by the high thermal capacity of the sea water and by the regional distribution of heat within the latter, also gives a directly practical reason for studying the temperature of the oceans (page 237).

Next to the regional charting of temperature (and approachable only thereby) the thermal problems now most pressing in the sea center chiefly around (*a*) detailed examination of the temperature cycles of regions that may be especially interesting from some particular standpoint; (*b*) the general variation in temperature with the seasons offshore, especially in the deeper strata; (*c*) the irregular non-seasonal fluctuations that are known to occur from year to year, or over periods of years, with their causes; (*d*) the thermal relationship between the surface of the sea and the air above it; and (*e*) the interplay of the several cooling and warming agencies. Under the last heading, empiric studies of the cooling effect of evaporation in different parts of the sea are now much to be desired. Quantitative analysis of the chilling that Arctic and Antarctic ice actually does (not theoretically may) bring about as it melts would be of great value. And tests are urgently needed as to whether the bottom water of the abyss receives an appreciable amount of heat from the

underlying earth, as some observations have suggested, or whether the slight rise in temperature recorded close to the bottom of the abyss in several cases is simply the result of adiabatic heating, because any warming from below would have a far-reaching influence on the vertical circulation in the deepest layers.

Small regional differences in the salinity of the sea water are secondary in the biologic complex as compared to the variations in temperature. However, it is now generally appreciated that they offer the most reliable of all qualitative indices to the broad-scale circulatory currents of the ocean basins and to the sources of different water masses. Illustrative regional problems now urgent in this respect include the entire oceanographic complex along and among the labyrinth of islands that fringe the coast of Alaska; the Asiatic fringing seas; the movements of the bottom waters of the Sulu Sea, as well as of other enclosed bowls; the expansions and contractions of the warm North Pacific drift with the seasons; the transferences of water through Bering Straits; the upwellings along California; likewise in the Humboldt current along the coasts of Ecuador and Peru, where hardly anything is known about the regularity or amplitude of the seasonal variations in salinity — to mention only a few of the more urgent cases.

Profiles of salinity even more than of temperature along several meridians for the Indian and Pacific Oceans, similar to those obtained by the 'Meteor' in the South Atlantic, are essential for working out the general circulatory systems of those oceans. First-hand information is also needed as to the exact combination of salinity with temperature from which to calculate the specific gravity, around the sub-polar margins (where the formation of oceanic bottom water is believed to take place) at the season when mass sinking may be expected to occur there (page 82). It is because of the practical difficulty of obtaining these data that we have so weak an observational basis for our theories of circulation in the crucial regions around the Antarctic and Arctic ice fronts.

Much more attention must also be paid to the processes that most directly affect the salinity of any given mass of surface water, namely, rainfall and evaporation. As has been recently remarked by a leading oceanographer, we still await an acceptable quantitative explanation for the fact that the waters of the North Pacific as a whole are considerably less saline than those of the Atlantic.

Quantitative measurements are also needed of the extent to which the freezing of sea ice actually increases the salinity—hence the specific gravity—of Arctic and Antarctic seas in the cold season, and how

the process of freezing alters the chemical composition of those seas. Conversely, a better quantitative measure of the freshening of the surface that is caused by the melting of ice in lower latitudes and of the difference in this respect between sea and glacier ice is essential before we can correctly estimate the importance of this process in the salinity complex.

Detailed knowledge of regional variations in salinity is also as essential as is that of temperature in every dynamic study of ocean currents, salinity being the other factor that determines the specific gravity of the water at any given time and place.

It is appropriate to consider next in what measure the raw data that are needed for the solution of problems of these categories have been gathered so far.

The temperature of the surface of the sea can so easily be measured, and the importance of a knowledge of ocean temperatures, not only to the geographer and to the biologist, but to the navigator as well (as evidence of the current in which he sails), was so early appreciated, that great numbers of such readings had been recorded along a great variety of trade routes by the first half of the last century. In fact, as early as 1873 Thomson spoke of the observations previously taken in the North Atlantic as almost infinite, while Petterman had at his disposal more than 100,000 temperature records for his paper on the Gulf Stream, published in 1870.

Many surface temperatures had also been gathered from the other oceans, thanks largely to Maury's efforts, and have been accumulated since that time by the hydrographic services of the various maritime nations. In short, our knowledge of the general distribution of temperature at the surface of most parts of the sea has reached a point where no far-reaching modification of the existing thermal charts for the surface is likely.

However, there is no part of the open sea for which the normal surface temperature is yet known for any season, in the detail demanded for the solution of many pressing problems, or the normal variations from season to season. And to trace the irregular fluctuations that exert wide-reaching effects within the sea and in the atmosphere, but of whose amplitudes we, as yet, know very little, is one of the most urgent tasks that now face the oceanographer. Here are formidable undertakings (though no technical difficulty is involved), for they required the collection of great numbers of records over a wide range of localities, with the subsequent analysis of the same.

The prevailing thermal state of the underlying waters has been established in its broad outlines. So rapidly, in fact, did it prove possible to learn the abyssal temperature, once attention was focused thereon, that the basic distribution of deep-sea temperature had become generally understood within

ten years of the time (in 1873) when Wyville Thomson had found it necessary to combat the view that the whole basin was filled with water at 4° Centigrade. So many deep-sea temperatures have subsequently been obtained in the North and South Atlantic that the general distribution, in the deeper layers, can now be plotted with some confidence for these oceans, though nowhere as yet in detail.

The recent work of the 'Carnegie' and 'Dana' has also made this possible for the bottom water of the Pacific, where, up to 1928, our only warrant for making generalizations outside certain restricted areas or along scattered profiles had been the great regional uniformity that characterizes abyssal temperatures in general, and the narrowness of the limits within which they have been found to alter over long periods of time. But even in the Atlantic basin, much more so in the Pacific basin, a vast amount of work remains to be done before a correct picture can be drawn of the general character and seasonal amplitudes of the regular alterations that take place from season to season in the temperatures of the water, below the stratum that comes within range of 'surface' readings, down to depths of 500 to 1000 fathoms.

Up to 1928 only about 100 serial determinations of temperature had been taken in the Indian Ocean to a depth greater than 500 fathoms; only six of these

to a depth greater than 1500 fathoms; although the last of these submarine contours encloses practically the whole of the Indian basin outside the continental slopes and slopes of the insular crests. And subsequent observations have been confined to the equatorial belt and to the African side. It is evident, then, that the thermal chart of the deep strata of that ocean cannot reach even to the elementary standard so far attained for the Pacific until serial records of the temperatures for all depths, surface to bottom, have been obtained over a much wider range of well-selected localities than has yet been done.

The gaps that still remain in our knowledge of the salinity of the oceans are far more serious than for temperature, both for the surface and for the deeps. Partly this is because only a fraction as many records have yet been obtained (accurate methods of measuring salinity, convenient enough for general use, are comparatively recent developments); partly because this feature of the water has engaged serious scientific attention through a much shorter period of time than has temperature; and partly because the considerable significance (in the study of circulation) of even the smallest variations, together with the unexpectedly complex regional inequalities that have actually been found to exist, make it less safe to deduce within significant limits the salinity of inter-

vening sectors of water from widely separated observing stations.

The only considerable areas for which oceanographers can yet claim even an outline of the normal seasonal cycle of salinity for the entire column of water, surface to bottom, are the parts of the northeastern Atlantic with its marginal seas (Norwegian Sea, North Sea, Baltic, and Mediterranean) that have been covered by the cruises of the international commissions; a much smaller coastwise sector off the east coast of North America between Cape Cod and Labrador; Californian and Japanese coastal waters, and the Javan and South China Sea where records were obtained quarterly for the period 1917 to 1920 Even for these regions we need a much closer knowledge of the seasonal fluctuations with the causes of the latter, especially of the irregular annual transgressions of one or another water mass which often play a disturbing (even destructive) rôle in the general economy of the sea.

In the ocean basins far from land modern requirements as to serial determinations of salinity have, with few exceptions, been met only by the major deep-sea expeditions, whose tracks, reasonably close-meshed in the Atlantics, have covered the Pacific and Indian basins (and especially the Southern Ocean) with a very sparse web indeed. Thus only about seventy such complete serial determina-

tions of salinity combined with temperature from the surface down to the bottom had been published for depths greater than 1500 fathoms in the Atlantic, north of the equator, about twenty north of 20° north latitude previous to 1928, nor had a single record of salinity been obtained below that level anywhere in the northwestern part, north of lat. 20° N. and west of long. 45° W., though the upper 500-fathom stratum of the North Atlantic had been examined, as to its temperature and salinity, on many occasions at many localities.

Thanks to the 'Meteor' we have today a better picture of the physics of the deep waters of the South Atlantic, in its regional and bathymetric aspects, than for any of the other ocean basins as a whole, an interesting illustration of the amount of exploratory work that a single well-planned and well-equipped deep-sea expedition can accomplish, while much information as to the southern extensions of the South Atlantic has recently been conbributed by the explorations of the 'Discovery I' and 'Discovery II.'

Until very recently the case was worse for the Pacific, where only thirty-one complete observations (salinity plus temperature) deeper than 500 fathoms had been published up to 1928 for all the vast area from the American coastline westward to longitude 180°; only 85 so deep for the entire Pacific

basin; and only seven deeper than 1500 fathoms. A large number of serials deeper than 500 fathoms (since published) have also been taken in the eastern margin of the Pacific within the last few years by the United States Bureau of Fisheries, and by the United States Coast and Geodetic Survey; but these have all been located close in to the American coast or around the Hawaiian Archipelago. And a dozen stations, extending out from the coast of Chile, gave the only accurate data, up to 1928, as to the salinity of the bottom of the Southern Pacific on the American side.

The whole southeastern part of that ocean had, therefore, remained nearly virgin, with respect to its abyssal salinities, until crossed by the 'Carnegie' in 1928–29; its northeastern basin hardly less so. And while the stations occupied by her on her last ill-fated voyage, and by the 'Dana,' in 1928, have made the salinity of the bottom waters of the temperate and tropical Pacific perhaps as well known as those of the corresponding belts of the Atlantic, blanks (so far as actual record is concerned) still remain in the northwestern as well as in the eastern tropical parts. Actual records of abyssal salinities for these regions are desiderata, to show whether the extraordinary uniformity in the salinity of the bottom water and the regular gradation from north to south revealed by the 'Carnegie' profiles is actually as char-

acteristic over the floor of the Pacific as a whole as now seems probable. Serial observations must be greatly multiplied and much more evenly distributed over the Pacific before meridional projections, in profile, of the salinity of that ocean, or circulation deduced therefrom, can be accepted as anything more than first approximations.

In the Indian Ocean we find a considerable number of serial records of the salinity of the superficial 500 meters of water for the equatorial belt, the coastal belt on the African side, for the northern part, and also for the sub-Arctic front which has been made fairly well known by the various Antarctic exploring expeditions. But not a single serial, even for this moderate depth, has yet been taken in the southeastern part, from longitude 80° E. right across to Australia, south of the equator. The determinations deeper than 1500 fathoms that have so far been made in the Indian Ocean have also been situated in the equatorial belt, in the eastern and western sides and south of Africa. When we turn to the Antarctic front of the eastern Indian Ocean, south of Australia, and right across the southward extension of the Pacific, we meet a *terra incognita*, uninterrupted (so far as knowledge of salinity is concerned) by even a single deep reading, from longitude 100° E. to the longitude of Cape Horn, and from latitude 40° S. right down to the ice edge. And

when we remember that knowledge of the Antarctic water complex is as integral in any sound understanding of the origin and movements of the deep strata of the Pacific as it is of the Atlantic, oceanographers realize but too well the inadequacy of the data on which we must perforce base our present views as to the physical and chemical conditions, as to the lines of dispersal from its source, and as to the circulation in general, of the bottom waters of the largest of the oceans, and the one that, in all its features, can be most truly named 'oceanic.'

The entire reconsideration of current views as to the circulatory movements of the different strata in the mid-levels of the Atlantic basins as a whole, especially as to the northward extensions of water from the Antarctic, and as to the regions of sinking and upwelling, that has been made necessary by meridional salinity profiles of the two sides of the South and Equatorial Atlantic, constructed from the 'Meteor's' data, illustrates the fertility of result that may be expected from equally detailed surveys of the salinity of other seas. And this applies not only to the great ocean basins, but to many areas of relatively small extent that may be especially interesting in the oceanic complex, from one standpoint or another.

To quote a few specific examples, some for waters easily accessible from headquarters of oceanographic

activity, others more remote: the mean state and seasonal variations still offer an attractive problem all along the Atlantic shelf of the United States south of Chesapeake Bay, in the Caribbean, in the Gulf of Mexico, and in the outflow from the latter through the straits of Florida; information essential for understanding the secular shifts in the Gulf Stream drift. Data as to the alterations that the highly saline water of the Sargasso Sea undergoes as it drifts outward from its center of concentration, with more detailed knowledge of the seasonal fluctuations in the African side that are associated with the seasonal migrations of the trade-wind belts to north and south, are equally needed before we can reconstruct the inter-movements of the surface waters in the tropical belt of the Atlantic.

Did we know as much about the salinity of the water off Morocco as we do of its temperature, we could better judge the importance (in the general Atlantic complex) of the water that wells up there from the deeps, in bringing up a supply of dissolved nutrients to help maintain the fertility of the surface stratum for plant life. The seasonal alterations in the salinity of the surface around South Africa, reflecting the alternate contractions and expansions of the warm Alguhlas and cold Benguela currents, also remain to be plotted in detail.

Particularly intriguing problems in this respect, in

the Pacific, are associated with the interchange of water into and out of Bering Sea; with the upwelling Humboldt current; with the mass transference from west to east in high southern latitudes; with the seasonal expansions and contractions of the warm Japan current; and with the coastal belt along southern Alaska. It is hardly worth while to specify particular lacunæ in our knowledge of the salinities of the Indian Ocean; the first chart of mean surface values for the basin of the latter that can be accepted as approximately correct appeared in 1928.

Within the polar seas precise measurements of salinity have been taken only by the recent exploring expeditions. Ice — plus stormy weather — has also limited satisfactory surveys of salinity around the ice fronts for the most part to the warm season. In the cold half of the year, when data are special desiderata for these belts, as bearing on the problem of the sites of the mass sinkings that supply the ice-cold and richly oxygenated bottom waters of the oceans, few observations have been obtained. This applies, for example, to the East Greenland current, to the Baffin's Bay source of the Labrador current, to Davis Strait, to the waters south of Greenland, to Bering Sea and to northeastern Siberian waters in the one hemisphere; to the entire Antarctic front in the other.

Ice has similarly prevented, to date, any winter

survey of the salinity of the Gulf of St. Lawrence, though this inland sea is close to the seaside laboratories of eastern Canada and of the United States. Neither had any detailed examination of Hudson Bay been attempted until 1930, when its midsummer state was surveyed by a Canadian expedition.

## 2. CIRCULATION

It is as essential for the oceanographer to understand the circulatory movements of the water if he is to comprehend any of the events that take place in the sea, whether biologic or geophysical, as it is for the meteorologist on land to understand the systems of winds.

Until comparatively recently this phase of physical oceanography was confined to the stage of exploration; first, by the fragmentary state of our knowledge of all the phenomena involved; second, by the lack of any method for calculating quantitatively, from data obtainable in convenient practice, the tendency that internal hydrostatics exert to set the water in motion. Lacking which it was impossible to analyze the relative importance of the internal archimedean forces of the water on the one hand, and of the external forces exerted by the wind on the other, as the causes of the great ocean currents. In fact, this still remains one of the outstanding problems in oceanography (page 96).

In practice, the study of ocean currents can never be divorced from that of the more static physical features of the water as represented by salinity and temperature, both because the latter give evidences of the former and because the circulation is largely responsible for the distribution of temperature and salinity as actually existing. We think of the transference toward the poles of great volumes of water that have been heated near the equator by the sun, of the return movements toward the tropics of water cooled around the Arctic and Antarctic fronts, and of the mass sinkings in high latitudes, because of which (as directed by the outlines of the continents and basins) the distribution of temperature in the sea does not vary directly with the latitude, but is asymmetrical, warmest in the eastern sides of the oceans in the northern hemisphere, in the western sides in the southern,[1] and the abyssal basins kept icy cold.

Cold currents also have a peculiar importance, because responsible for the drifts of ice from the Antarctic and Arctic to melt in lower latitudes, with all that this entails as to sea chilling, effects on terrestrial climates, and so forth, while this same melting process produces circulatory effects in the near-by waters that have been the subject of much

[1] This is controlled to some extent by differences in the efficiency of alternate summer warming and winter cooling, *in situ*, along the windward and leeward sides of the continents.

dispute. It is, therefore, impossible to understand the thermal problems in the sea if we do not understand the phenomena and causes of its circulation, and *vice versa*; this applies equally to the problems of salinity; likewise to the regional and bathic variations in the concentrations of oxygen as well as of the various solutes, and to the maintenance of conditions approaching equilibrium with regard to the alkalinity, and so forth, of the water. Circulation, of one kind or another, also plays an active part in the events of submarine geology, by sorting and transporting sediments, attacking shorelines and slopes, and so forth. No argument, indeed, is needed to justify the study of ocean circulation from the geophysical standpoint, for here we face an earthly phenomenon of the first rank. Currents in the sea also intrude constantly on the attention of oceanic biologists; partly because this would be true of anything that controls the temperature of the water, but also as agencies active in the migrations and dispersals of a wide variety of animals and plants. This phase is of great concern to students of the problems of the marine fisheries. The mobility of the waters of the oceans (with their high specific gravity) also concerns the biologist as making possible the planktonic existence of many groups of animals and plants, while permitting other categories of animals to lead a stationary existence fixed to the bot-

tom, where they depend on the waters to bring their food to them, instead of upon their own powers of locomotion to carry them to their prey (page 145).

The knowledge of currents that is needed by the biologist calls, furthermore, for examinations of special regions so detailed that we commence to see the circulatory bases for vital economy in only a few areas, all of them near land; the North, the Norwegian and the Barents Seas, for instance; the Baltic, the Mediterranean; the Gulf of Maine; the Gulf of St. Lawrence; the Californian and Japanese coastal waters.

Currents, like temperatures (page 119), also bear directly on human affairs *via* the disturbing effect that any sporadic departure from the normal state must have on the temperature of the water, hence on the temperature and barometric pressure of the overlying air, to be reflected in weather abnormalities over the neighboring lands (page 242). The importance of ocean currents in navigation as they assist or impede passing ships, and as the relative directions of current and of wind affect the heights and shapes of waves, also as the agencies responsible for the menace to the traffic lines by icebergs, is self-evident.

There is, in short, no field of study of sea or of its contents that is not immediately concerned with the circulation of the water. We must emphasize that

this concern extends to every type taking place, an to every force, external or internal, that is able to s the water in motion, because every class of circula tion that exists has far-reaching effects in all th fields just mentioned, while, because of the almo perfect fluidity of water, a variety of forces produc motion within it. Furthermore, every circulator problem involves both the observable events an their causes.

For the purpose of these remarks circulatory phe nomena in the sea may be divided into (*a*) tidal, se in motion by the gravitational attraction of th sun, of the moon, and of other heavenly bodies; an (*b*) non-tidal, including all other currents or dis turbances of whatever sort.

The study of the tides is now so admirably care for by the tidal surveys of all the more importan maritime nations that it will be omitted from thi discussion.

For convenience, the non-tidal currents may, ir turn, be divided into (*a*) the progressive horizontal (*b*) those with a prevailing vertical component, anc (*c*) the non-progressive oscillations which do more work in the sea than is generally appreciated. But it is necessary to realize that all three of these types may, and usually all three of them do, combine tc produce the movement actually existing in the open sea at any given time or place. The first of these

groups covers all the more apparent ocean currents, also the slower mass drifts, whether at the surface or in the deeps. The second group refers to the mass sinkings and updrafts (equally important if less obvious elements in the closed system); likewise to the violent churnings that take place along certain sectors of coastline, as, for example, at the mouth of the Bay of Fundy, and over some of the most productive fishing grounds; it also refers to the turbulent effects of tides and waves in general. The third refers to wave-motion, including, besides wind waves, the so-called 'tidal waves' which in reality are set up by volcanic action or by earthquakes beneath the sea; and submarine waves mentioned below.

Every student of the sea has fully realized the importance of the horizontal ocean currents in the scheme of things; so has every intelligent seaman, for the first important application of currents to be appreciated was the navigational. The problems of this phase of oceanic circulation that now seem most pressing unfold themselves along three chief lines; (1) What is the normal current system of the ocean in all its parts, in all its depths, and at all seasons of the year? (2) What is the magnitude of the variations from this normal state, and how often do they happen? (3) What are the motive forces for the continuing system of currents in the sea and for the deviations therefrom?

From the dawn of the art and science of navigation, ship captains have realized that knowledge of the currents was necessary for the safety and expedition of their voyages; by the middle of the last century the gradual collection and digestion of vessels' log books had given the navigator a rough picture of such of the major currents as affected him the most, especially in the North Atlantic. Even though it was chiefly by suiting the sailing routes to the prevailing winds that the use of Maury's and more recent sailing directions expedited voyages, it is certain that advantage taken of the prevailing current was partly responsible for the consequent savings, so long as sailing ships continued to carry the bulk of the world's commerce. And while full-powered steamers now run more independent of the current, continued collection of such data has been considered so important that the Hydrographic and Meteorologic Offices of Great Britain, of Germany, of Holland, and of the United States had together gathered more than 27,000,000 notes on the wind, weather, surface temperature, and surface drift of the sea, up to 1904, while a vast quantity of such data has been accumulated since then.

And yet, no one who stops to consider the vast areas covered by the oceans, the great expense of special expeditions, and the difficulty of making direct measurements of the current anywhere except

lose to land and in very shoal water, will be surrised that even the surface currents can yet be ictured only in a very generalized way. This is due n part to the nature of the information available om log books, in which any leeway that the ship nay have made is usually included in the recorded drift.' But a more serious difficulty is that ocean urrents do not progress like smooth-flowing rivers, ut are constantly varying in velocity and direction, ddying (even temporarily reversed by the wind) in way so complex that it is not yet possible to state he details for any part of the sea at any season of the ear. Furthermore, surface data, taken by themelves, may give a very erroneous picture of the acual circulation, because a knowledge of the movenents of the underlying water is equally essential. n this last respect reports from passing ships do not elp us at all.

Since it has not proved feasible to use current neters frequently enough in deep water, or at staions enough there to be of general value, it is necesary to turn to indirect sources of information to learn he direction of the horizontal flow in the deeper ayers. The sorts of data from which this drift may e deduced are various. The distribution of oxygen ives us some information. So does the distribution of the different kinds of sediments on the bottom; also the geographic distribution of various plants and

animals. But far the most reliable indices to the movements of water masses below the surface — apart from measurements taken with current meters — are their temperatures and salinities. Hence it was not until a satisfactory deep-sea thermometer was invented and a method both accurate and convenient for measuring the salinity (or the specific gravity, for the one can be calculated from the other) that science was in a position to gather empiric knowledge of the movements that geographers had long postulated for the bottom waters of the oceans.

With these tools at command, one is able, by tracing the expansions of cold or of warm water, of high salinities or of low, to recognize such things as Arctic or tropical currents; land water fanning out off the river mouths; lines of dispersal for the highly saline waters that result from evaporation at the surface in certain enclosed seas (Mediterranean and Red Seas) as well as in the trade-wind belts; updrafts from the underlying strata; regions where water, chilled to a high specific gravity, sinks obliquely from the surface; regions of active turbulence where the surface is chilled, the bottom warmed; and so forth. The evidence of salinity is especially instructive with respect to deep currents, because in this respect a body of water below the surface is altered only if it be forcibly intermingled with water of some

other character, whereas cold water may be warmed, or warm water cooled by radiation, without any such mixing. And while the knowledge of currents to be obtained from temperature and salinity (each weighed *per se*) is strictly qualitative, up to date this has been almost our sole reliable clue to the movements of the waters of the deeps.

Nor must the modern development of quantitative methods of studying ocean currents lead to any neglect of the simpler qualitative evidence afforded by temperature and salinity *per se*, because the two lines of attack open up different aspects of the circulatory problem. The first throws light on the direction and velocity of flow prevailing at the time of observation, and to be expected as long thereafter as conditions continue stable. But when we find, let us say, a tongue of cold water extending down along the Grand Banks from the north of Newfoundland, with bergs floating in it, we see the result of events that have been taking place for some time previous: i.e., we glimpse oceanographic history. And by plotting these simple physical features of the water, periodically, it is possible to follow the relative contractions and expansions of different water masses as long as these continue. Thus in physical oceanography, as in every one of the geophysical sciences, the qualitative-descriptive method of study must proceed hand in hand with the quantitative, if we

are to gain a just picture of events as they actually occur in nature.

In this case, as is usually true of broad-scale phenomena, the dependability of the results rests largely on the number of observations taken. And as we have to do with dynamic phenomena, rather than with static, the more nearly simultaneous the observations can be made the better. Naturally, these technical requirements have best been met in the more frequented and more fished parts of the North Atlantic and of its tributary seas. Qualitative studies of the currents at different depths have, in fact, been prosecuted so intensively in limited areas in the North Sea, in the Norwegian Sea, in the Bay of Biscay, in the Straits of Gibraltar, in the Gulf of St. Lawrence, in the Gulf of Maine, around the Grand Banks, also in and off the straits of Florida that at least the characters of the prevailing systems of motion have been worked out there, surface to bottom. This applies also, if in less degree, along the coasts of southern California and around Japan; but nowhere else as yet.

When we turn to the ocean basins, outside the margins of the continents, we find crying need for the raw data (temperature and salinity) for current plotting (pages 55, 59). Lacking this, we still fail to comprehend more than the most general aspects of the drifts over the floors of the abyss — movements that are as important a part of the picture from every

point of view (except the navigational) as is the circulation of the surface. And our ideas as to the dominant drifts and interchanges in the mid-strata of the ocean basins are only now crystallizing. This is especially true of the vast and lonely expanses of the Pacific, which have been traversed by scientific expeditions only at long intervals, and along tracks far apart; where, consequently, and for the Indian Ocean, knowledge of the underlying circulation might be expected to lag far behind that for the Atlantic, though their closure to the north (complete for the Indian Ocean, nearly so for the Pacific) simplifies their circulatory characters.

Risings and sinkings of the water are not as apparent to the casual observer as are the horizontal drifts. In fact, movements of this sort are, as a rule, so slow that they are not to be detected — much less measured — by ordinary instrumental observation, but only indirectly by their effects upon the temperature and salinity of the surface waters of the regions in question. Since they are not of direct interest to the navigator (omitting the mythical or more actual whirlpools in narrow straits, and so forth) their existence was not recognized until theoretic discussions of the circulatory systems of the oceans made clear the necessity for assuming the existence of something of the sort, and until they were deduced from observations on the winds.

Modern oceanography is, however, much concerned with the oblique updrafts and sinkings that are now known to take place on a vast scale, because it is certain that the presence of a thick stratum of water in the abyss, colder than the mean temperature of the underlying crust of the earth, is the result of mass sinkings, near the poles, of water that is cooled and so given a high specific gravity at the surface. Conversely, we need more than our present sketchy view of the compensating updrafts, known to prevail along the coasts of Morocco; off Southwest Africa; off California; off Ecuador, Peru, and Chile. From what depths do these chiefly draw? What are their velocities, their seasonal fluctuations, the volumes of water involved? Just how do they control the physical characters of the upper strata of water, and what is their effect on the vital economy of the seas where their physical effects are greatest? Only for the California upwelling can we yet answer these questions even in the roughest way; while the rôle played in the hydrologic complex of the South Pacific by the South American — Humboldt current — upwelling still offers one of the most attractive problems in general oceanography.

Important in this connection is the rôle of these updrafts as conveyors, to the surface, of water that is rich in dissolved plant nutrients. It seems clear enough (in fact, numerous analyses of phosphates,

nitrates, and so forth, establish) that as the carcasses of animals and plants are constantly sinking, the chemical compounds to which they finally decay would tend to accumulate in the mid-levels out of the reach of the photosynthetic plant world were there no such updrafts and no churnings of the water. For diffusion takes place too slowly in motionless water and on too small a scale to account for the regeneration of dissolved foodstuffs that is known to occur in the upper stratum. But in the sea interchanges (vertical as well as horizontal) of water masses having different qualities are constantly being brought about by upwellings, eddyings, and turbulences of all sorts, with effects agreeing with what would happen if the coefficient of diffusion were high. That is to say, while water, denuded of some of its load of chemical nutrients is carried down, other water masses that have been enriched during their sojourn below are brought up.

The fact that planktonic plants have been found in depths so great that they cannot be supposed to carry on photosynthesis there does not argue against the view that this replacement of barren water with rich is a vital factor in the maintenance of organic fertility in the sea, because they have been taken most abundantly under regions where the surface flora (hence the sinking carcasses) are also most abundant, suggesting that this abyssal plant plank-

ton really represents a saprophytic community—just as when we grow rhubarb, and so forth, in our cellars in the dark. Empiric tests of the actual events are, however, much needed, because theory has far outstripped observation in this field; needed especially with regard to the degree of obliquity of the mass updrafts. These are often named 'upwellings,' but it is certain that this is a misnomer if taken to imply direct vertical movement, for in all probability the angle of ascent is, in most cases, so slight that if represented in profile a great exaggeration of the vertical scale is needed to show any departure at all from the horizontal.

Closely associated with the mass movements just mentioned are the problems of turbulence in the shoal marginal seas where most of the important sea fisheries are concentrated. In such situations this type of circulation is a physical factor of the very first rank, because it does the same work there, in bringing rich water up from the bottom to the surface, and in maintaining the circulation of oxygen, that the great rising currents do for the ocean basins far from land. In high latitudes the interchange of water between surface and bottom that is brought about by turbulence also plays an active rôle in the thermal complex of shoal seas, by bringing cold water from the deeps up within the direct influence of the sun and carrying warm water down in sum-

mer, while assisting the loss of heat by radiation in the same way in winter.

The activity of turbulence at any given time and place is determined by the interplay of many factors: strength of the tidal current, for instance; shape of the bottom, contour of the coastline; strength of the wind; height and shape of the waves, likewise by the degree of vertical stability given to the water by the vertical distribution of specific gravity prevailing at the time. Turbulence, moreover, varies from hour to hour with changes in the tide and wind. Thus wide regional and seasonal variations may exist in this respect between stations only a few miles apart, making local investigations extremely complex, especially since the turbulent movements are of such a nature as to preclude direct measurement. But interpretation of regional variations in the thermal and saline cycles of shoal seas in mid and high latitudes (where there is the greatest abundance of plants and animals), and of many events in the life histories of fishes and other animals, as well as of the periods of multiplication for the planktonic plants, depends so directly on knowledge of the varying degrees of turbulence that this general subject deserves much more attention than it has received. We see in the Bay of Fundy a striking example of turbulence as the determining factor, to mention but a single notable example.

The distribution of oxygen in the sea is so closely associated with the general problems of vertical circulation that it is best mentioned here. It seems certain that the intake of oxygen occurs exclusively at and near the surface, (*a*) in the surface film, or within the upper few feet where air bubbles are entrapped by breaking waves, and (*b*) throughout the upper illuminated zone where plants carry on photosynthesis; no sources are known from which the water can absorb free oxygen in the deeper levels. Quantitative data as to the rapidity with which any deficiency in oxygen is renewed from these sources of supply (particularly the efficiency of the latter out in the open sea) are therefore present desiderata. The relative importance, from the standpoint of oxygen intake, of coastlines of different characters, with their different types of wave action and of turbulence, offers an interesting problem. How effective a source of oxygen supply for the surrounding neighborhood is, for instance, a rocky headland upon which the surf beats constantly? We have yet to learn how deep simple turbulence is able to maintain the oxygen supply close to the saturation point in different regions under different conditions.

The underlying waters, contrasted with the surface stratum, can be described as the zone of oxygen consumption, for they are constantly being robbed of their supply of this dissolved gas, not only by

animals in their respiration, but by the oxidization of the decaying carcasses of animals and plants, as these sink down. Measurements of the actual rate of impoverishment under the varying conditions actually existing in the sea are much wanted in connection with a variety of biologic problems.

If there were no means of renewing oxygen from above, the underlying water would soon be absolutely stripped of this vital necessity, as the deeps of the Black Sea actually are. And within the last few years it has been found — (notably by the 'Carnegie' and by the 'Dana') that the mid-depths are, in fact, decidedly poor in oxygen in mid and low latitudes in the Pacific — also over large areas in the tropical Atlantic; so poor, indeed, that one is inclined to marvel at the wealth of animal life that exists there. But, underlying this oxygen-poor stratum, the bottom waters of the ocean basins carry a much richer load of this gas. In the present state of our knowledge, it seems that the only way in which stratification of this sort can be maintained is by sinking currents carrying down into the deeps, water that has become saturated with oxygen near the surface in high latitudes, coupled with consumption in the mid-stratum, rapid enough nearly to denude of its oxygen the water that is brought up from below by rising currents. But we urgently need information as to whether these mass sinkings of oxygen-laden

water are as strictly confined to the Arctic and Antarctic Seas, in their respective winters, as now seems probable; also how this water continues so nearly uniform in oxygen over vast areas on the sea floor in spite of the wide local variations in abundance of animals that are constantly consuming it there; and how far it is safe to deduce the drifts for the deepest stratum from the variations in the concentration of oxygen that do exist there.

The relationship that the paucity of oxygen in the equatorial mid-strata of the Atlantic bears to the drifts, toward the equator, of sinking water from mid-latitudes north and south, that are revealed by the 'Meteor's' profiles, remains to be worked out. Similarly we await a satisfactory interpretation, in terms of circulation, of the much more general poverty in oxygen of the mid-strata of the Pacific. The local factors (e.g., abundance of plants and animals, amount of decomposition of organic matter taking place at different levels) responsible for the very notable divergence between the quantitative distribution of oxygen and that of salinity, as revealed by the most recent meridional profiles of the oceans, also offer interesting problems. And the very rapid falling-off of oxygen, with depth, in the upwelling waters off California where extremely low values have been found close below the surface, introduces the question how far this state is generally character-

istic of the other regions where updrafts take place on a broad scale.

Certain problems associated with oscillatory movements of the sea next deserve a word Two classes of phenomena come principally in question here; one, the ordinary storm waves (often complicated by tidal churnings), the other, the internal boundary waves or vertical undulations at some mid-level that winds and other forces are known to set in motion, and that have also been observed on occasions when no apparent cause could be ascribed to them.

Although the importance of learning the depth of storm-wave base, and the efficacy of storm-wave oscillations down to that level, as transporters of heavy materials, is obvious from the geologic standpoint, very little is yet known (except for shoal waters) about the absolute depths to which it is effective. For example, can we assume as representative of the sub-tropical belt of the Atlantic as a whole the conditions prevailing on the Challenger Bank, off Bermuda, where considerable masses of calcareous algæ are rolled to and fro, often enough for these to stay alive on all sides, down to a depth of fifty fathoms or so, presumably by storm waves? How much deeper is effective wave-base in the Antarctic where swells might, theoretically, travel right around the globe without meeting any obstacle — and perhaps actually do so? What is the

velocity of such oscillation at different depths, when set in motion by storm waves of different shapes, lengths, and so forth, and traveling at different speeds? For that matter the shapes and run of the surface waves themselves offer an interesting field; in fact the stereogrammic studies by recent expeditions, notably those of the 'Meteor,' have given the first exact topographic pictures of the very complex corrugations into which the surface of the sea is thrown by the wind.

Our present knowledge of submarine boundary (or internal) waves in the open oceans has hardly advanced beyond the realization that such things exist and that they may be set up by a variety of forces. We need to learn what conditions give rise to progressive boundary waves, what conditions to standing waves; their periods; their relation to the free tidal wave; and their rôle in general in the sea, including such points as their frequency in different regions at different seasons, their vertical amplitudes, their lengths from crest to crest, and so forth.

Perhaps the most pressing of the broad problems in physical oceanography today, made so by its direct bearing, not only on events of all sorts in the sea, but on land climates as well, is that of the irregular fluctuations in the ocean currents, with the causes of such events.

It is certain that if the present scheme of ocean

circulation were materially to change, the climates of the continents would soon differ widely from the present state; and for the worse, so far as man's welfare is concerned. The effect of the ocean currents on land climates is so much a commonplace, stressed in every textbook of physical geography or meteorology, that we need only cite (a classic example) the effect of the Gulf Stream or North Atlantic drift in making habitable the most northerly parts of western Europe (reflected in the fact that the mean temperature for January is about 40° F. higher in northern Norway than is normal for that latitude), contrasted with the opposite side of the Atlantic, where the icy Labrador current from the north so chills the climate of the coastal strip all along Labrador as to make agriculture impossible at latitudes corresponding to those of Ireland and England. Any variations in the currents that shift the previously existing distribution of temperature in the oceans, as any considerable alteration is bound to do, will have a still more direct bearing on animal and plant life in the sea; one almost certainly destructive to some species, but perhaps temporarily favoring the production or extending the geographic boundaries of others. The almost total destruction of the tile fish off the east coast of the United States in 1884, presumably by a flooding with cold water, is probably to be explained on this

basis; similarly the immigration of fishes of temperate thermal affinities into high latitudes that were reported as taking place north of Europe in 1922, and in the northwestern Pacific in 1922–24.

In a general way, the waters of the central parts of the open basins can be described as extremely stable in their physical character from year to year, and over long periods of years, if compared to the atmosphere. The close correspondence between temperatures and salinities recorded at several stations in mid-Atlantic by the 'Challenger' in 1877–78, and at near-by localities by the 'Michael Sars' in 1910, the 'Bache' in 1914, illustrates this fundamental constancy. Around the oceanic fringes, however, and especially toward the outer boundaries of the prevailing mass drifts, conditions are far less constant, not only seasonally, but as a result of wide-scale, but irregular, expansions or contractions of water masses of different physical characters, or because of shifts in their relative locations. The most widely heralded event of this sort that has come under human observation in recent times (because its effects or accompaniments both on land and in the sea were destructive) was the abnormal development of the warm drift from the north along the west coast of South America in the winter of 1925, accompanied either by a slackening of the cold Humboldt current (or upwelling) which normally bathes these

shores, or, perhaps, by its diversion offshore. During that same winter and the preceding autumn a westward deviation of the cool Benguela current was reported as similarly accompanied by an expansion toward the south of the warm Guinea current along the west coast of South Africa. Sporadic events of the same sort have also taken place in high latitudes, within the memory of men now living. Between 1892 and 1897, for example, there occurred what has been described as an 'outburst' of ice from the Antarctic, sending many floes and icebergs northward into the southern ocean. A similar outburst of Arctic ice was reported in 1901, when Barents Sea was full of pack ice up to May, while ice is said to have come closer to the Murman and Finmark coasts than usual. On the other hand, an expansion of warm Atlantic water was reported to have taken place into these northern seas in the summer of 1922.

It is true that departures from the normal so noticeable as these are rare events, and up to recently it has only been these major departures that have forced themselves on general attention. It has long been known, however, that smaller fluctuations do take place from year to year in the boundaries and extensions of the warm North Atlantic drift. Similarly, the International Ice Patrol has found that the interrelationships of the Labrador and Gulf

Stream currents around the Grand Banks are not alike in any two successive years, either in the seasonal schedule or in the volumes, temperatures, or velocities of the two currents. And these differences are reflected, not only in the yearly variations in the amount of ice drifting down past the Grand Banks, but in the tracks followed by individual bergs. In fact, wherever ocean circulation has come under continuous observation for a period of years, it has been found to vary, more or less, in a non-periodic, and up to date in an unpredictable, way.

There is, as yet, no general agreement of scientific opinion as to the causes of these variations, for all that has yet been possible, in any individual case, has been to show an apparent correlation between the event and some outstanding solar or other cosmic happening. Some students have regarded such fluctuations as due, in the last analysis, to variations in the amount of energy (i e., heat) that reaches the earth from the sun, but others maintain that these solar variations are insufficient to account for phenomena known to take place. And even if the solar-control theory be accepted, the intervening mechanism by which variations in the strength of the sun's radiation might be translated into the variable pulses and curious dislocations shown by the ocean drifts is still to be worked out. Does this take place *via* the medium of changes in the prevailing strength

and direction of the winds, caused by shifts in the locations of the centers of high and low atmospheric pressure? Does more or less active heating of the waters around the tropic belt send greater or lesser volumes of warm water poleward, or is the Antarctic shelf perhaps a cradle for world-wide disturbances in the circulatory systems of the oceans, as at least one eminent oceanographer would have us believe?

Or must we conclude, as do some students, that the solar variations are too small, and the ability of the sea to absorb and smooth out their effects too great (owing to the great capacity of water for heat), for fluctuations of the currents to be explained in this way? In that case the theory that periodic changes in gravitation are responsible, caused by the regular secular changes in the relative positions of earth, moon, and sun, must be critically weighed.

The possibility that events taking place around the sub-Antarctic belt, where vast masses of ice break off, may exert far-reaching effects, translated in the end into climatic variations in distant parts of the earth, brings to our attention another problem with which physical oceanographers have long been much concerned; namely, the relative importance that melting ice plays in the complex of factors that keep the oceanic circulation in motion. Here the present need is not so much for rehashing the old

arguments, *pro* and *con*, as for much more extensive investigation actually around the ice edge than has yet been feasible. At first sight this might seem an especially favorable subject for experiment under laboratory control, for one can easily put a piece of ice in water and observe what takes place as the ice melts. But one of the reasons why the relative efficacy of melting ice as a causative agent for ocean circulation is still a matter for dispute is uncertainty as to whether the results seen in laboratory tanks, or in some small fjord, do actually simulate the conditions that prevail over the broad expanses of the open ocean, closely enough (quantitatively as well as qualitatively) to be accepted as representative of what happens in nature.

The regional and descriptive phases of oceanic circulation lead naturally to a discussion of the present state of knowledge and of theoretic opinion as to the interplay of forces that maintain this circulation. New viewpoints in this field have followed the recent development of quantitative methods of estimating the relative efficiency of the two major forces most obviously concerned; namely, the internal hydrostatics of the water itself on the one hand, and the frictional effect of the winds on the other. Until mathematical expressions were made available to take account of the various factors (e.g., wind fric-

tion, internal friction, regional differences in specific gravity, deflective force of earth rotation), quantitative estimation of the velocity of currents, in the sea, could be made only by the use of current meters. But, generally speaking, the use of these instruments is confined to shoal waters near land, i.e., to situations where tidal currents are not only strongest, but are veering if not reversing; hence where they so constantly confuse the picture that continuous observations over long periods are necessary before the dynamic or other broad-scale movements can be distinguished from the local and temporary ones.

Many such current measurements have been taken on special tidal surveys along the various coastlines; likewise from lightships in the North Sea, in the Baltic, and off the east and west coasts of North America; also in the straits of Florida where Pillsbury carried out his classic studies of the volume and velocity of the outflow from the Gulf of Mexico. But, by the nature of the case, quantitative estimation of the drift of the whole mass of water for any considerable area of the open ocean demands more generally applicable, hence deductive, methods. For such advances in this field as have yet been made, we must chiefly thank the theoretic development of ocean physics that has followed Bjerknes's contributions to hydrodynamics, chiefly at the hands of Scandinavian oceanographers; combined with

Ekman's mathematical discussions of the characteristics of wind-driven currents.

The raw data that are needed for the dynamic investigation of areas that may be selected as test cases are not only easily obtained, but are of a sort that have long been collected in ordinary routine, i.e., a record of the temperature and of the salinity at a sufficient number of depths-levels, at a net of stations sufficiently close, and taken nearly enough simultaneously to allow horizontal projection of the dynamic state prevailing over the area, as a whole, that is under study. And mathematical procedure by which such projections may be arrived at from primary data has been so simplified that it can be mastered by any physical oceanographer. However, it has not yet been developed to a point where it is possible to include in the equations all the factors that are pertinent. And until this stage is reached, certain very serious sources of possible error will remain, which prevent this method from being the 'cure-all' that its simplicity and mathematical defensibility might suggest. In the first place, the results can never be more than relative to some other mass of water which may be taken as the base for calculation. Consequently, unless the velocity of the water chosen as this base be measured, or unless this water be known to be stationary, the calculated result cannot give the actual current. In favorable

cases, with serial records of temperature and of salinity for a sufficiently dense network of stations, it may be possible largely to overcome this difficulty. But we urgently need empiric tests, on a much broader scale than it has yet been possible to make, of the magnitude of the error that is introduced into the calculations by the fact that even the deepest water layers are actually not stationary.

The contour of the bottom also introduces a factor that can seldom be stated numerically, for if a current set in motion by internal hydrostatics strike a ridge of the sea floor, or a coastline, it may be given a character quite different from that calculated for the 'free ocean,' of which oceanographers speak so glibly, but which no one of us will ever see.

Therefore, we urgently need some general expression of the degree to which such calculations are applicable to regions where the depth differs much from station to station, or, to compensate for this confusing factor of depth, some numerical allowance more rational than the arbitrary corrections that have so far been proposed.

Similarly, it is not yet possible to include, in a satisfactory way, in the equations the friction between water layers or masses that differ in velocity, and while it is certain that this frictional effect depends on the state of motion of the water or air (leading to the concept of 'eddy viscosity'), knowledge of

its exact effect in the circulatory complex is in its infancy. Neither have mathematic expressions yet been developed to include the immediate and varying effect of the wind in given cases, though there is general agreement now as to the fundamental nature of wind currents as controlled by the deflecting effect of the rotation of the earth.

To check the magnitudes of these several sources of error, and of others that future studies may bring to light, regional dynamic examinations of the sea should be carried on hand in hand with any direct means that may be feasible for discovering the velocity and the direction of the current at the time, whenever and wherever opportunity allows. In the few cases where such a comparative examination has yet been undertaken, the agreement between the calculated drift and the type of circulation indicated by other lines of evidence as prevailing at the time has been close. Thus, in several instances the tracks followed by individual icebergs, drifting down past the Grand Banks of Newfoundland, have corresponded to the dynamic current charts made simultaneously by the ice patrol cutters closely enough to warrant the hope that such calculations will be of practical service to the patrol. Similarly, a recent dynamic analysis of the velocity and direction of the outflow from the straits of Florida, based on observations taken by the United States Coast and Geo-

detic Survey Steamer 'Bache' in 1914, agrees in general with earlier measurements with current meters. Dynamic circulatory tendencies calculated for different seasons of the year for the Gulf of Maine have been corroborated by various other lines of evidence, direct as well as indirect, at least in their broad outlines, so, too, for the Norwegian Sea; for the North Sea, and for the northern sector of the Labrador current. In short, many oceanographers believe that we now have at hand a tool by which it is possible to approximate, numerically, the movements of the whole mass of water at a given time for situations where regional variations in specific gravity indicate a calculated drift so strong that it can hardly be masked by the probable error of the method, i e., where regional differences in hydrostatic pressure are great enough to produce a current of considerable velocity.

In any study, in this general field, it is also essential to remember that while regional inequalities in the specific gravity of the water, by setting up archimedean forces, will set the water in motion, the existence of such inequalities itself results in most cases from other precedent motion of the water. Examples are the introductions into various regions of water alien in physical character, by currents such as the Arctic discharge *via* the Labrador current, the fresh discharge from rivers, or surface waters driven by

the wind from afar. Discrimination between what is cause, what effect, is therefore integral in any attempt to deduce, from dynamic calculations, the existing circulation.

Some different quantitative procedure is needed, furthermore, for situations where the dynamic gradients are slight. A method based on the amount that the surface temperature departs from the value normal for the latitude and season, and on the thermal effects of evaporation, recently worked out at the Scripps Institution for Oceanography, and applied with promising results to the waters off the coast of California, may prove generally applicable to other regions where upwelling takes place on a broad scale; it may also provide a useful check on horizontal velocities deduced from dynamic gradients in other regions.

It is essential to hold firmly in mind the realization that such methods, or any others, are after all only a means to an end; i e., tools of research, not the ultimate aims of the latter. In the fields of physical oceanography the perfection of quantitative technique and the further amplifications that are to be expected are not to be followed *per se*, but to serve two chief lines of attack upon circulatory problems. In the first place, it now seems reasonable to expect that they will lead to a rapid advance in our knowledge of the state of circulation actually prevailing

over large ocean areas and at all depths from the surface downward, especially for parts of the sea where there is a wide regional variation in specific gravity from place to place. In fact recent dynamic studies of the northeastern Atlantic by Scandinavian oceanographers have already materially altered the prevailing concept of the northern boundaries of the general North Atlantic drift and of its extension toward the Norwegian Sea, though these matters are still far from settled. And similar studies of the waters off Alaska have added greatly to the existing knowledge of the circulation of that part of the northeastern Pacific. During the summer of 1928, a Danish expedition worked northward along West Greenland into Baffin's Bay, while simultaneously the United States Coast Guard carried out a general dynamic survey of the circulation of the region of Davis Strait with fertile results. We similarly expect from the numerous observations taken by the 'Meteor,' in the Equatorial and South Atlantic, a general circulatory picture for that ocean, for comparison with the schemes deducible from the distribution of temperature and of salinity or from the drifts reported in ships' log books. And data obtained by the 'Carnegie' will add much to knowledge of the circulation of the Pacific.

From the standpoint of ocean physics as a whole, however, the greatest service to be expected from

such developments in quantitative analysis is that here, at last, we look forward to a means of numerically testing the relative efficiency, as a motive power for ocean currents, of one of the two great forces that have usually been invoked as the underlying causes for the existence of a continuing non-tidal circulation in the sea. We refer to the broad-scale inequalities in the local specific gravity of the ocean waters that are maintained by heating at low latitudes, chilling at high, combined with the regional differences in salinity that result from river inflow, from evaporation, and from rainfall.

In this field, the task immediately urgent is to determine, for as many sectors of different currents as possible, and for as many different ocean areas, whether the internal hydrostatic forces at work are, or are not, quantitatively sufficient, and do, or do not, act in the direction proper to produce the general type and velocity of circulation that other lines of evidence have shown to prevail. More specifically, examinations of particular sectors of the so-called 'Gulf Stream,' of the Labrador current, of the East Greenland, the Benguela, the Alguhlas, or the Japan currents (among others) may be expected to show (when checked with direct measurements) how far such highly developed and definitely localized drifts receive impetus from internal archimedean forces acting along their courses, or how far some

other force (i.e., the winds) must be invoked to explain their existence and persistence. Certain dynamic studies carried on in the northwestern Atlantic since 1926 have had this as one of their immediate objects; the results, to date, justify the extension of explorations with this definite aim.

Before the frictional effect of the winds as a major motive force relative to that of internal hydrostatics can be finally established (scientific opinion has long swung first to the one, then to the other), wind currents must also be analyzed more searchingly and on a much larger scale than has yet been possible. The mechanical principle in question here is simply the downward propagation, into the water, by friction, of motion given to the surface film by the direct frictional drag of the wind. But it awaited a mathematical genius to prove that the earlier concepts of wind currents were erroneous because they did not correctly allow for the deflective force of the earth's rotation, or explain the peculiar spiraling of such currents with increasing depths. And the fact that the wind drift actually recorded has often failed to coincide, by many degrees of azimuth, with the theoretic requirements shows that more critical quantitative treatment is still needed to establish some numerical expression for the effects of vertical density gradients and of the contour of the bottom (which have, to date, confused the cal-

culations of the velocity, volume, and direction of the current that any given wind will set up in shoal water), as well as to make sure that all the pertinent factors have received due weight in the equations in given cases. Known methods of estimating the effect of a coastline in the direction of a wind-driven current account for some of these apparent discrepancies, but others remain to be explained.

When we turn to the chief regional problem of the wind as a motive force — i.e., how far the great trans-oceanic drifts under the trade-wind belts, and around the Antarctic Ocean are, in fact, kept in motion by the wind, or in what proportion wind friction combines here with internal hydrostatics, — we find few data at hand for quantitative treatment.

In these and similar cases theoretic discussion of physical potentialities can provide a series of accurately solved type problems. But here (as in the case of tank experiments with melting ice) the conditions under which such discussions apply are far simpler than those prevailing in nature: in nature, furthermore, factors are involved that it has not been possible to account for, satisfactorily. The dynamic oceanographer is therefore urgently concerned, at present, with determining, by critical examination of selected parts of the sea, to what extent these theoretic discussions actually meet the needs of the case, and to develop them to meet these needs.

## 3. Penetration of Radiant Solar Energy into the Sea

This subject is mentioned above, in connection with the penetration of heat. But the visible part of the solar spectrum is also so important in the vegetable and animal economy of the sea that the biologist constantly turns to the physicist for information as to the depth into the water to which light rays of different wave lengths penetrate with intensity great enough to serve plants in their photosynthesis, or to affect the tropisms or metabolism of animals. The theoretic coefficient of absorption of light by pure water has been calculated many times. What is now needed is empiric test of what does actually happen in the sea, at different localities, with the sun standing at different heights above the horizon, and under the widely differing conditions of turbidity and wave action that actually prevail. In this, as in other phases, the stage of quantitative measurement has been reached some time since; the next rational step is the accumulation of data over the widest possible range of latitudes, locations relative to the coastline, varying abundance of suspended silt or plankton, different seasons of the year, states of the surface of the water, and so forth, and then subsequent syntheses to make clear the order that prevails.

## 4. Chemical Problems of the Sea

As the whole cycle of matter in the sea depends upon the fact that the latter is filled with salt water (a solution, not a mere mechanical mixture), it follows that chemical problems are more or less inherent in every phase of sea science. Consequently the reader will find repeated references to various chemical questions in the sections on oceanic biology and on submarine geology. In the present chapter we wish simply to outline the sorts of problems that center around two chemical questions that are fundamental in oceanography, (*a*) precisely what is sea water, and (*b*) why is it that the major furrows of the earth's surface are filled with this particular saline solution, not with some other, or with a variety of others?

Growing evidence that the rarer substances in the solution may be the most significant, from the biologic standpoint, has made it clear that the published analyses of sea water can be accepted only as first approximations, for it seems certain that sea water carries every element in solution, some of them perhaps entirely ionized. Several institutions, both in Europe and in America, are now devoting much effort to sea-water analyses, but a vast amount of work remains to be done before any approach to an adequate picture can be gained of the average levels of concentration, and of the periodic and regional

variations in amount of the rarer substances. As knowledge increases, first one and then another of these attracts attention. At the present time interest in this field centers largely around the concentrations of phosphates, of the salts of nitrogen, and of silicates because of their service as nutrients for pelagic plants: around calcium, both as a material for skeleton formation and because of its import in many of the chemical reactions that proceed on a large scale in the sea. Recent tests for iron, cæsium, rubidum, and for radio-active substances might also be mentioned.

Adequate methods have already been developed to measure the amounts that now seem significant of some of these in the water. But we still lack a satisfactory technique for determining the nitrates that are present in solution. And as others of the rare solutes attract attention, refinements of technique will be needed, because chemists have, in these cases, to do with solutions so attenuate that they are close to the lower limit at which accurate analysis is possible. In fact, some substances are at present known to exist in sea water solely because they have been detected in the bodies or skeletons of marine animals and plants, which could only have obtained them from their aqueous environment. As examples of this we might mention the vanadium recognized in the blood of Ascidians and of Holo-

thurians; the cobalt in the tissues of lobsters and mussels; the nickel in mollusks; and the lead that has been found in the ash of various marine organisms.

The ionic ratios of different substances in the solution (a matter of much interest from the chemical standpoint) is also to the fore at present.

However, our increasing knowledge of the variations in particular solutes that exist in the sea, or of such phenomena as supersaturation of the water with calcium carbonate, or that it is frequently far from being in equilibrium with the atmosphere with regard to gas tension, must never blind us to the extraordinary uniformity in gross composition of the water in all parts of the open ocean. Whether the sample be taken in the Atlantic, in the Pacific, or in the Indian Ocean, in high latitudes or in low, the total solutes are found to be about 54 per cent chlorine; about 31 per cent sodium; about 4 per cent magnesium; about 1 per cent potassium; 1 per cent calcium; and about 0.2 per cent bromine, with about 8 per cent of sulphate radicals, about 0.2 per cent of carbonate radicals. And this uniformity in the relative proportions of the commoner constituents is now so well established that it is customary, not only to regard sea water as a substance practically constant in its composition, but in practice to employ the concentration of one group of its salts as a dependable index to the total saltness.

The variety of conditions and the vast areas throughout which such uniformity prevails make this one of the outstanding phenomena of geochemistry. Not only do the oceans cover more than two thirds of the surface of the globe, but in depth, temperature, light intensity, and pressure they run the whole gamut from warmth, bright illumination, and freedom from any superimposed weight save that of the overlying atmosphere, to icy cold, permanent darkness, and subjection to pressures of 800 atmospheres and upwards per square inch. Yet the solution that fills them is certainly the most uniform in composition of any substance common on our planet aside from fresh water and the atmosphere. And most geologists, arguing from the composition of the skeletons of marine animals that have lived in the past, together with that of sedimentary rocks which were laid down at different periods under the sea, believe that comparatively little change has taken place in the sea water itself (apart from its total salinity), except that during the earlier geologic periods the proportion of lime salts in solution may have been smaller than has been the case in more recent times.

This uniformity in time and in space extends, furthermore, to the precise proportion that total bases bear to total acid radicals. In spite of all the life-processes in the water that are constantly tend-

ing to alter this proportion (and do actually so alter it within narrow limits) by adding or withdrawing carbon dioxide and calcium, or by altering the relative proportions of the normal carbonates to the acid bicarbonates in the solution, the balance is so closely maintained at all places and at all times in the open sea that the alkalinity never rises above or falls below the narrow limits within which organic life (as regulated to marine conditions) is able to exist. This phenomenon is as important in ocean economy, and as deserving of the closest chemical examination, as is the stability of the alkalinity of blood serum in human physiology.

To offer, in explanation, that the sea water is buffered against wider fluctuations is to beg the question, for it in no wise accounts for the 'how' or 'why.'

To unravel the interplay of factors which keeps sea water always so nearly the same, and has so kept it for long ages in the past, is one of the most attractive tasks of research in chemical oceanography now before us, because a wide variety of wide-scale processes are as constantly tending to disturb this uniformity. To begin with, sea water (although it has certainly received much of its load of 'salts' by erosion from the land) is very far from being a mere concentration of river water, for not only does the latter vary from river to river in its chemical composition,

but as a whole it differs widely from sea water in kind. Consequently, the discharges of rivers tend to alter the composition of the sea water off their mouths as well as to dilute it. Various explanations have been proposed for the chemical events by which the preponderance of calcium and of carbonates, which characterizes river water, is so uniformly altered into the preponderance of sodium and of chlorides that characterizes the sea water, everywhere and at all times, even under the most diverse conditions. But we believe no one would seriously maintain that any of the explanations are adequate.

It seems clear that we have here to do with something more fundamental than a mere withdrawal of lime by shell-bearing organisms, and of carbon by photosynthetic plants, such as would allow sodium and chlorides to accumulate out of proportion. In fact, recent work suggests that this characteristic state obtains close in to the mouths of great rivers, although the diluting effects of the latter may be apparent for long distances; i.e., that the transition is more sudden with respect to the chemical composition of the water than with respect to its saline concentration. The view that sea water owes its preponderance of chlorides chiefly to the accumulation of the products of volcanic eruptions must be thoroughly tested before any opinion can be expressed as to its soundness.

In the second general category of events that are constantly tending to alter the chemical composition of the water in all parts of the sea are those dependent upon the vital activities of marine animals and plants within it. Obvious examples of this are the withdrawals by the former of lime and silica from the water for the manufacture of their skeletons.

No less significant, in the chemical complex, are the withdrawals, by marine plants, of salts that serve as nutrients: the plant life that we see in the water is the visible product of this draft. The alterations in the state of the water that result when the carcasses of these plants (and the bodies of the animals that feed upon them) go back into solution, after death, are equally significant.

Basic problems, that we may single out for mention in this connection because of their rôle in the general cycle of matter in the sea (page 256), center around the chemistry of lime and of carbonic acid, bound up with the degree of alkalinity of the water. The chemist here meets a very complex series of reactions in which gas tension between water and atmosphere at different temperatures, withdrawals of lime and carbon by organic agency, precipitation of lime, re-solution (which goes forward at different rates for different lime salts, and according to the amount of free carbon dioxide in the water) and alterations in the degree of ionic dissociation of dif-

ferent salts in the solution, all play a part. The importance of this general field in its relation to submarine sedimentation, and to the accumulation of lime deposits generally, as well as in its more strictly biological aspect, is touched on in other sections.

The chemical aspects of the precipitation of calcium carbonate in tropical waters, where large amounts of the lime out of the water are contributed to the sea bottom, are now being taken up afresh. If this precipitation be chiefly mechanical, as now seems likely (page 29), we need to learn which of the various reactions that have been suggested as the potential causes are actually operative on a large scale in the sea: if bacteria be the active agency, the problem is biochemical.

No general agreement has yet been reached as to the rapidity with which calcium carbonate is dissolved in the sea under the conditions actually existing, especially for deep water. That limy shells, sinking down, may entirely dissolve before reaching bottom if the water be deep, has been widely postulated to account for the fact that there is a lower limit of depth below which there is little accumulation of lime sediments. Solution must also be taken into account in connection with the fact that the percentage of lime has been found to decrease in the oceanic sediments, from the uppermost layer

downwards, in various localities. Recent data (by the 'Meteor'), showing a slightly higher proportion of bases in water next the bottom than in overlying strata, also point from another angle to solution of lime oozes as taking place on a significant scale. But we have little knowledge as to the actual details of this process at great depths, in different regions. It is certain that the last word has not yet been said as to the solution of lime from coral formations in tropical waters, or from the accumulations of precipitated calcium there.

Such problems introduce the basic question of the efficiency of normal sea water as a solvent, not only for lime, but for silica, for volcanic substances that accumulate on the sea floor, and for various refractory organic substances. Solution of a wide variety of minerals is also constantly taking place all around the shores of the continents, in combination with the processes of mechanical erosion by the waves and currents. And while this solution is slow, it is not only unceasing now, but has been unceasing for past geologic ages. In short, the total amount of material dissolved in this way has been enormous. Furthermore, some recent observations with regard to the concentration of silicates in the water raise the question whether solution of even these refractory materials may not take place rapidly enough to produce regional differences in the amount of silicates

in the water, according as different sectors of the coast contribute more or less to the sea.

Chemical problems equally fundamental are inherent in present-day studies of the ocean floor, for the oceanographer is directly concerned with the whole gamut of reactions that take place in the abyssal depths of the sea, it being an open question whether many of those that have been proposed (although doubtless falling within the range of potentialities) are actually of the importance that has been accredited to them on theoretic grounds. With regard to the sea bottom, as well as with regard to the water itself, first rank might be given to the problems of lime chemistry, with ramifications too numerous to list in this report. It is not unreasonable to hope that chemical studies of events taking place in sea water today may give a clue to the mode of formation of dolomite in the sea in the past. The reactions that accompany the formation of phosphatic concretions and of glauconite on the bottom also need further examination, while the problem of the chemistry of the deposition of iron on the sea floor is a major one and to date practically untouched (page 34). So, too, the chemistry of the natural distillations of organic materials in the bottom muds that are now widely believed to have been responsible for the formation of petroleum and other hydrocarbons.

As already remarked, we have still to learn the

chemical character of the water that is entrapped within the sediments, a very important matter because the alterations that take place there in the solid materials depend upon the alkalinity, carbon dioxide content, and so forth, of this water.

Recent observations have also led oceanographers to turn their attention afresh to the regional variations in the amounts of oxygen and of nitrogen gas in the water, as indices to various physical and biological events there. Here the immediate need is for thorough regional and bathymetric survey, for this alone can give a sufficiently descriptive picture of the existing state.

The list of chemical problems that center around sea water might be lengthened indefinitely. In all of them, as is so usual in oceanography, two phases are involved. First, the theoretic potentialities must be determined, and these have naturally been the subject of much discussion, leading to substantial agreement with regard to some. The significant task is then to discover in what proportion the theoretic reactions do actually take place in the sea, in what order, and how induced; a task made difficult by the low concentrations of the solutions with which it is necessary to deal.

# CHAPTER IV

## THE RELATIONSHIP BETWEEN OCEANOGRAPHY AND METEOROLOGY

THE relationship between oceanography and meteorology is of an order different from that between it and geology or biology, because meteorologic events do not take place within or under the water, as geologic and biologic do. But the state of the surface of the sea so directly affects that of the air above it that meteorologists are much concerned with certain phases of oceanography, while, on the other hand, the temperature, humidity, and movements of the air are as constantly tending to modify the physical state of the water below it. The economic importance of investigating the interdependence between air and sea is discussed in a subsequent chapter (page 237). The present section, contributed by Professor C. F. Brooks, is concerned with its more strictly geophysical phase.

Oceanography can contribute much to meteorology, for nearly three quarters of the atmosphere rests on the ocean, the heated surface of which provides all the water vapor for the air and controls its temperature to a considerable height. The oceanic factors involved in this discharge of vapor and in this heat regulation are not only the temperature of

the surface, but also the salinity of the surface, the storage of heat below the surface and, through convection, its availability to the surface, and the horizontal movements of these waters in currents and drifts.

Since, because of their high thermal capacity, the surface waters of the oceans contain enormous amounts of available heat, they exert a steadying and moderating effect on the climates of the world. The oceans take in and give off heat slowly and regularly, and temperature conditions of the water tend to persist a long time and to travel slowly. Sea temperature observations across the ocean indicate the persistence of unusual warmth or coolness of extended masses of water for months — even for a year, or perhaps two — as, carried in the various currents and drifts, they make the circuit of the North Atlantic or cross the Pacific. This leads one to believe that (quoting Petterson), 'besides trying to predict the extremely variable state of the fickle atmosphere, one should give more attention to the conservative element of meteorology, the surface sheet of the ocean, where changes at one place may be observed months before' they reach, and affect the weather of some other region.

Indirectly, the sea has another effect on world weather. Differences in vapor content and in air temperature determine the contrasts in density and,

therefore, in pressures of the atmosphere between different portions of the oceans and between the oceans and the lands. And these pressure differences cause the winds. Thus, knowledge of the temperatures of the surface of the sea, and their background, the storage of heat in the sea and the currents that carry this stored heat, is fundamental to meteorology.

The planetary belts of temperature, pressure, wind, and storm that dominate the world's climates are best developed over the sea. The general homogeneity of the sea surface favors approximately equal humidities and temperatures along any parallel of latitude as the sun goes through its seasonal swing northward and southward. And this even distribution of humidity and temperature (except near the continents) favors rather uniform belts of pressure and of winds, with their fair weather where the pressure is high (in latitudes about 20° to 40°) and their showery or stormy weather where the pressure is low, near the equator and from high middle to subpolar latitudes. Furthermore, the flatness of the surface of the ocean permits the maximum development of rotary storm movements, such as the winds of a West Indian hurricane.

Where lands lie athwart these wind and storm belts they receive a full measure of oceanic weather on their windward margins, as on the North Pa-

cific coast of North America. If no high mountains form a barrier, marine influences are felt hundreds, even thousands of miles inland, as in Europe and the eastern United States. Winds and storms from the Gulf of Mexico and other tropical waters of the western Atlantic thus traverse eastern North America and provide the rainfall for this vast agricultural region.

The continents throw a diverse land surface across the latitudinal belts of moisture, temperature, pressure, winds, and storminess fostered by the oceans, and thereby interrupt the continuity of these belts. The low humidities of the air over the land, the high temperatures in summer and the low ones in winter, favor strongly contrasted pressure-conditions in the warm and cold seasons. In summer the continental air is expanded and a considerable quantity is forced to overflow over the cooler oceans; in winter the air over the land is chilled and contracted so much that great masses of air return aloft from over the sea. Thus continental air pressures tend to be low in summer and high in winter, while oceanic air pressures tend to be high in summer and low in winter. The major areas of high and low pressure, which are essentially the oceanic and continental sections of the planetary pressure belts modified, as just outlined, by the contrasted humidity and temperature conditions, have long been known as the

grand centers of action. They are the large areas of high or low pressure around and from which or around and into which the prevailing winds blow.

Recalling that only one of the half-dozen centers of action by which the eastern half of the United States is dominated either in winter, or in summer, is continental, the importance of the oceanic centers is at once apparent.

If these centers of action went through their seasonal transformations with consistent regularity year after year, their nature and underlying causes would not give us much of a challenge; but such is not the case.

It is, of course, easy to surmise that if appreciable variations in sea surface temperature over large areas occur irregularly, there should be, through the changes in vapor discharge to the air and in the temperature of the air, a greater favoring of high atmospheric pressure when the sea is colder, and of low pressure when it is warmer. European meteorologists have long recognized this relation in the northeastern Atlantic. Two apparently significant examples may be cited in the western side of that ocean from the Gulf Stream. A body of unusually warm water coming through the straits of Florida in January, 1916, on spreading over the western Atlantic south and east of the northeastern United States appears to have been responsible for eastward

deflection and intensification of many western low-pressure areas that reached the Atlantic seaboard, accompanied by prevailing northerly winds, cold weather, and frequent snows. In the same manner, unusually warm water passing through the straits of Florida in October, November, and December, 1925, may be assumed, paradoxically, to have favored the storminess and coldness that prevailed during these and later months in the eastern United States.

Recognizing the importance of a knowledge of the surface temperatures of the western Atlantic, from the meteorological viewpoint, the United States Weather Bureau, the Canadian Meteorological Office, the International Ice Patrol, Clark University, and the American Meteorological Society have, within the past three years, installed sea water thermographs to record surface profiles regularly across the area from the Grand Banks, Bermuda, and Porto Rico westward to Canada and the United States, and southwestward to Cuba, Honduras, and the Panama Canal Zone. A body of accurate sea-surface temperature data is thus being assembled for the study of such progressive movements and persistence of sea-surface temperature departures as may exist in the Gulf Stream and Antilles currents, and for comparison with the state of the atmosphere. But this is only an introduction, while this regular

recording of surface temperatures should be extended to include determinations as well of the heat storage in the top twenty-five to one hundred meters, of the horizontal movements of these waters, and of the degree to which atmospheric humidity, temperature, and distribution of atmospheric pressure depend upon the temperature of the ocean surface.

We may also point out that oceanographic expeditions to the less traveled seas offer excellent opportunities, at little extra cost, for obtaining a wide variety of meteorologic data, for problems other than that of the interrelation between atmosphere and ocean surface.

# CHAPTER V

## LIFE IN THE SEA

DIFFERENCES, in the disciplines employed, and in the nature of the immediate problems attacked, make it convenient to classify this branch of science under three headings: (1) Oceanic Zoölogy and Botany, (2) Marine Physiology, (3) Marine Bacteriology.

The first of these is chiefly concerned with the ways in which the basic conditions of life in the sea are made manifest by the diversity in structure and in habits of animals and plants. This includes such subjects as taxonomy and its relation to geographic and bathymetric distribution; the dependence of successful reproduction, growth, migrations, and so forth, on definite factors in the marine environment, embracing also the general subject of life histories; the adaptations that enable various groups to populate particular parts of the sea; the interdependences of different species of animals, and of animals as a group on plants; the environmental factors that govern plant growth; and all problems in cognate fields.

Marine physiology covers the study of the general and basic conditions and phenomena of life that are common to marine animals and plants; of the vital reactions between the cell, or aggregate of cells, and the external environment; of the interactions be-

tween the various tissues and the blood or lymph; also of the physiological adaptations of unicellular and multicellular organisms to variations in the sea-water environment.

The heading 'Marine Bacteriology' covers all the activities of bacteria in the sea.

## 1. Oceanic Zoölogy and Botany

These headings cover the same fields of study in the sea as do the corresponding sciences on land; hence students have precisely the same reasons for pursuing the former as the latter. Consideration of the characteristic differences between marine and terrestrial life likewise makes it clear that the pursuit of oceanic zoölogy and botany, as contrasted with terrestrial, also opens certain special avenues for the general advance of biology.

There would be ample justification for pursuing the marine branches of the sciences in question from the descriptive standpoint alone, if from no other, to increase our knowledge of the kinds of animals and plants that exist upon this planet. For it is certain that a formidable proportion of the inhabitants of the sea (i.e., two thirds of the earth's surface) still remain to be discovered, while our knowledge of many others that have already been found is far from complete even as to their structure, let alone their activities. And as long as new animals are to be found, we

may be sure the biologist will seek their discovery, for he dare neglect no opportunity to explore the actual manifestations of life, whether by land or by sea. Collecting expeditions at sea are therefore urgently needed, especially along the less frequented coasts, and in the mid- and abyssal ocean basins; in this way rich harvests of fishes, crustaceans, mollusks, and so forth, never before seen, are brought to light from time to time. Hand in hand with field work of this sort must go the study (in museums ashore) of the collections so gathered.

The situation in this respect is on precisely the same plane in the sea as it is on land, where the need of fresh collections from little known regions, to enlarge our knowledge of birds, reptiles, or of insects, is so commonly appreciated that it is not difficult to obtain support for such undertakings. It is only because the variety and beauty of the fishes, crustaceans, and other groups of animals in the oceans, and the interest that attaches to their life histories, are appreciated by so few that it is not equally easy to find support for collecting expeditions for them. All of which applies equally in the case of oceanic plants.

At the present time much attention is being paid to the geographical distribution of the marine inhabitants, with reference, for example, to the latitude, to the strength of the sunlight, and to the tem-

perature, for we still fall far short of an adequate knowledge even of the broad outlines of such matters. The problems that may here be grouped are not easy either of definition or of solution if we attempt to advance beyond the primary descriptive stage, while as yet we have hardly entered even into this introductory phase in the case of most of them.

This applies even to the horizontal distribution of marine animals and plants — the aspect of the general geographic problem that is most readily attacked — because serious gaps in the faunal mosaic still remain to be filled in for extensive sectors, of coastline as well as of sea bottom. As taxonomic studies become more and more critical it proves that many of the identifications of the past, on which generalizations as to the faunal relationships of different areas have been based, must be revised. And this whole field of study is vastly complicated by the involuntary migrations to which so many marine animals and plants are subject, and by which whole communities may be (and often are) carried to regions which they cannot permanently colonize. A case in point — perhaps the best known example of broad scale transport to unfavorable regions — is that of tropical pelagic organisms to fatally high latitudes by the agency of the Gulf Stream. And every gradation is to be seen in this respect, from sporadic drifts, of occasional individuals, far outside

their normal ranges, to the opposite extreme where a supply is so constantly brought from some far-off source that a permanent community is mechanically maintained in parts of the sea where the species in question cannot reproduce themselves. A familiar example of the latter category is afforded by certain pelagic worms in the Gulf of Maine; perhaps also by the rosefish (*Sebastes*) around the coast of Greenland.

In this connection one's thoughts turn, naturally, to the series of problems that group around the bathymetric distribution of the animals and plants of the deeper zones of the oceans in different regions, at different times of the year, and at different times of day, for discoveries recently announced suggest that some of the views currently held are incorrect. And the differences in habit between adults and young in many cases (perhaps in all) added to the differences at different latitudes, so complicate this whole field that the correct description which must precede any sound analysis still lies far in the future.

Perhaps in no phase of oceanic biology would advances be more welcome than in that concerning the whole question of the productivity of the sea under the conditions that actually exist at different times and places, and of the factors that control the amount of organic production that does in fact take place. The obstacle to advance in this field has not

lain in any failure to appreciate its importance: on the contrary the literature on this subject has grown to formidable dimensions, while numberless counts of diatoms, copepods, fish eggs, and other things have been made — also enumerations of organisms of one sort or another living on given areas of the sea bottom in various regions. But it has proved so difficult to devise technique that would be comparable for different times, for different places, and for different groups of animals, that no really adequate method of general attack has yet been found: even to measure a thing apparently as simple as the volume of organic matter present in the water at a given time or place. Nor are counts of individuals comparable except in the rarest cases, because different stages in growth (different sizes) are involved.

Inseparable from the general question of the abundance of marine life is that of the factors and events that control the success of organic production. The question, what is responsible for the wide variation between good and poor years of production for various fishes, is very much to the fore at present in fisheries biology. As this is discussed on page 217, we need only remark here that the same problems arise in connection with every marine animal or plant, and that our knowledge in this whole field is still practically *nil*. As yet we know little of the interrelationships of different species or

groups of animals in the sea beyond the obvious fact that some prey upon others, but we may be certain that in many cases interrelationships of less obvious sorts are vital links in animal economy. And it would be as easy to multiply this list of urgent biologic problems for the sea as for the land; as impossible to make a complete enumeration, for even if one could conceive of such a list as covering the field today, every advance in knowledge would open new vistas that one cannot now foresee.

Among the more special reasons for encouraging marine zoölogy and botany, as contrasted with terrestrial, one might first mention that of convenience. It is, in fact, safe to assume that this, of itself, would be reason enough for biologists constantly to turn to the sea in the future, as they have in the past, for subjects of investigation, whether in surveys of the gamut of animal form or for the study of particular problems in the various fields of morphology, ecology, and so forth.

The fact that the ocean is the home of the oldest and simplest types of various phyla, that it supports representatives of every phylum, and that it is the exclusive home of at least one of the latter [1] explains why the comparative anatomist requires access to marine organisms. The comparative embryologist

[1] Of a second, also, if the ctenophores be considered a separate phylum.

profits for the same reason; for him certain marine forms — selachians, echinoderms, ctenophores, and many others — are classic material. For work in experimental embryology, the eggs of echinoderms, nemerteans, certain marine annelids, mollusks, and fishes are especially adapted both because they can be obtained in unlimited quantities, and because the fact that they are laid and will develop in sea water over considerable ranges of temperature makes them suitable for experimental procedure. Contrast this with the scarcity in number and inaccessibility to experiment of the eggs of mammals. Except in the water, furthermore, no eggs are laid without extraneous protective devices.

The student of egg-cleavage, cell-lineage, and allied subjects has benefited accordingly by the favorable subjects afforded by marine animals in the past, and it is certain that the embryologist of the future will similarly benefit as new lines of attack open in his particular province. In the same way the abundance of life along the seashore offers particular advantages to the student of ecology; as, for example, through the opportunity that is open for the investigation of highly complex colonial developments, and manifestations of the divisions of labor among lowly organized groups in the sea. It is, in fact, the unique opportunity for biological studies in many and diverse fields offered by various marine

organisms which has led to the establishment of the marine biological stations that have played so large a part in the modern development of theoretical as well as of observational biology in general.

It would be easy enough greatly to extend the foregoing statement of concrete problems that face the zoölogist or botanist in the sea, and of the directly practical reasons why biologists in general should turn to marine organisms, were there any need of so doing. The chief purpose of this chapter is, however, to show how differences between the conditions of life in the sea and on land open roads along which oceanic and terrestrial biologists can advance toward their common goal from somewhat different angles, allowing the convergent approach that has often been productive in science in the past. We refer to the simplicity, constancy, uniformity in time as well as in space, and favorability as an environment for living substance as constituted on this planet, of sea water as contrasted with air. Thanks to these characteristics, we may hope to trace the underlying relationship between the living plant or animal and its physical-chemical surroundings, as well as between different groups of organisms, in a more direct way in the sea than is usually, if ever, possible on land. In many respects, therefore, the former is the more favorable natural laboratory of the two, for

investigations into the underlying principles that govern animal and plant ecology.

Certain of these peculiarities of the sea as a home for life have often been signalized of late. But a restatement here is called for, to justify the thesis just set forth.

The most obvious advantage of the sea water, contrasted with air as the home for a substance (protoplasm) composed chiefly of water, is that it is an aqueous solution. The physiologic-morphologic bearing of this fact, with the resulting contrast between all terrestrial organisms on the one hand and all aquatic plants and animals (sea or fresh water) on the other, is as obvious as it is direct. All animals and plants in the sea being free from the water-needing complex by which every animal and plant living in air is bound, none needs or has developed any of the protective adaptations which their relatives on land have been forced to elaborate in order to guard against the failure in the supply of metabolic water which, for them, is apt to be fatal, even if of the briefest. We see nothing, for example, in the sea in any way comparable to the storage of water by the stomach of a camel or in the stems and leaves of certain desert plants. Neither is it necessary for the external covering of any aquatic organism to serve it as the protection against a loss of water from inside the body to outside, which is the one absolutely essential

function of bark, rind, skin, and so forth, on land. Freed from this compelling factor, living substance may (as one contributor to this report has pointed out) even remain naked in the sea, which is never possible in the air: or if it cover its outer surface with a skeleton, it may employ a great variety of materials; lime, silica or even strontium, cellulose, agar, chitin and spongin, as well as solidified proteins.

Equally direct, though perhaps less obvious, is the relationship between water and the geographic distribution of marine as compared with terrestrial animals, all parts of the sea being equally open to all living creatures, so far as this factor is concerned. Contrast this with the state existing on land where it is a commonplace of schoolboy instruction that the supply of drinking-water, together with the dampness of the air, largely controls the kinds of animals or plants that can inhabit different regions of the earth.

Still further simplicity of metabolism is made possible for marine organisms by the thermal uniformity of the medium in which they live, as contrasted with their relatives on land, which must (by and large) be able to accommodate themselves to wide and rapid variations in the temperature of their own bodies (because temperature controls the rate of so many chemical reactions) or else must be able to guard themselves against such changes. It is com-

mon knowledge that the activities of animals and plants of the first of these two categories (i.e., those with internal temperature nearly the same as that of the surrounding air) are greatly limited in regions where the temperature range of the air is wide from hour to hour, from day to day, or from season to season. A familiar example is the sluggishness of snakes, turtles, and so forth, and of many insects, in cold weather as contrasted with their activity in warm. And while the maintenance of an even body temperature (actually a high one) independent of the temperature of the surroundings does not necessarily require any general modification of the gross anatomy, it does involve metabolic adjustments so delicate that any disturbance of the regularity of its control is apt to be fatal. It also requires that the surface of the body be in some way insulated against the passage of heat, as by the fur of mammals, the feathers of birds.

Marine life is free from the need of such thermal adaptations and protections because the changes in temperature at any given place in the sea average not only very much smaller than they do in the air, but very much slower. Throughout most of the ocean deeps, in fact, the temperature is practically unvarying from year's end to year's end. And while shoal waters in high latitudes do show considerable alterations in this respect with the change of the

seasons, it is only close to the surface that such changes are great. Consequently, any animal can reach a nearly constant thermal environment even there, merely by swimming down a few fathoms to avoid extremes of summer heat or of winter cold, as many fishes actually do in their regular bathic migrations.

On the whole, therefore, marine animals have not found it necessary to provide the specific protection against thermal variations in the environment that is provided by a self-controlled body temperature. That is to say, the discovery of warm blood has never been made in the sea. All the warm-blooded animals that now live there, whales, seals, walrus, and so forth, are descended from warm-blooded terrestrial ancestors. And in maintaining their body temperatures these marine mammals not only enjoy no advantage but are under a positive handicap because the high thermal capacity of the surrounding water makes this a much more difficult task for them than it is in the air. It is to meet the resultant problem of insulation that seals as well as whales are enclosed in their envelopes of blubber; bulk that is of no direct service except as protection against outside cold, but is in other ways actually detrimental because its presence requires more food and increases the difficulty of propelling the body through the water. Contrast with this the happy condition of the

fish which needs fat not at all for the purpose of insulation, but only as a storehouse for energy that can be drawn on even to the point of total exhaustion if famine so require.

Judged from the standpoints of numerical abundance and ability to people all parts of the sea, marine mammals as a group have not been as successful as the fishes, although both the metabolic activity and the thermodynamic efficiency of the organism as a whole are far higher in warm-blooded than in cold-blooded animals.

It is because of the thermal constancy of the sea water that marine animals as a whole, whose internal temperatures are practically those of their surroundings, rising and falling as the latter rises and falls, do not pass through the alternating periods of activity and stagnation that on land are characteristic of cold-blooded animals, except those of the tropics. In the sea, as a general rule, each species is attuned to a certain optimum range of temperature in which it passes most of its life, but within which range various phases of its vital activities, especially of its reproduction, are directly controlled by temperature changes. Otherwise expressed, cold-water fishes may be as active as warm — witness the trouts and salmons or the herrings. When, as sometimes happens, a sudden change in the temperature causes widespread destruction (page 72), Nature's provi-

sion for the reëstablishment of the species in the sea is simple, being merely a production of many more eggs and young than can survive under normal conditions.

These thermal differences between the aquatic and the terrestrial environment make the study of the relationships that the activities of the organism on the whole (as distinguished from its several constituent tissues) bear to temperature far simpler among marine or fresh water than among land animals. And the control that temperature exerts over the life processes makes this a very important subject in relation to such questions as geographic and bathymetric distribution, migrations, breeding seasons, and rates of growth, to mention but a few.

The comparative opacity of sea water to solar radiation, especially to the part of the spectrum that carries most of its energy, protects all of the inhabitants of the sea, except such as live close to the surface, from the lethal effects of sunlight, thus freeing them from the need of developing any opaque covering for protection from the sunburn against which every terrestrial animal must in some way guard its living substance. Because of the resultant rapid gradation in the strength of the light from the surface of the sea downward, and because of the ability of marine animals to escape light by sinking, the sea, therefore, offers a far better opportunity than

does the land to study the whole category of tropisms caused by light stimulation; also the natural economy of animals that live permanently in total darkness as well as the problems that center about animal luminescence.

This applies equally to the study of pigmentation, because one of the chief factors that controls its development among land animals — light — plays so much less important a rôle in the sea, allowing pigment the more directly to reflect internal metabolic activities there. A case in point is the fact that while animals living in darkness on land are usually colorless, those of the ocean abyss, below the influence of the sun's visible rays, are usually intensely pigmented, often a velvety black, a difference reflecting in the one case a loss of pigment previously developed by ancestors that lived in sunlight, in the other case the development of pigment untrammeled by light, its causes as yet unknown.

Another contrast having far-reaching biologic effects is that between the specific gravity of the medium in which organisms live on land — the air — and in the sea. Thanks to the fact that sea water has almost the same specific gravity as protoplasm (or protoplasm as sea water if one prefer) no marine animal or plant needs the mechanical support against the pull of gravity that every organism of any considerable size must have on land if it is not to col-

lapse of its own weight. Thus no alga needs, or has developed, a rigid woody skeleton. And as marine animals have never required strong frameworks to support themselves, their internal or external skeletons can be adapted entirely to other ends, such as protection (as in the case of many mollusks) to provide stiffness as among the horny corals, to maintain body form against resistance of the water while swimming or for the attachment of muscles as among fishes and crustaceans. Comparison of the frame of a whale (which suffocates of its own weight if left stranded on the beach by the ebbing tide) with that of an elephant or a dinosaur shows at a glance how much less is necessary in the one case than in the other. In spite of their great muscular power, even the largest sharks have still feebler and wholly cartilaginous skeletons without any hard bones, while even a more striking case of strength without framework is afforded by the giant squids, animals proverbially active, swift and muscular, though with only the rudiment of any sort of skeleton. No morphological development of this sort would be possible on land. As a corollary of this, there is no gravitational limit to the size of animals in the sea, the only theoretic limit being their need of taking in, through the surface (and usually through a very small part of it), enough food to support the entire bulk and enough oxygen for its vital requirements. With this

relief from the force of gravity, the sea supports animals as large today as it ever has, and heavier than any that have existed on land.

Freedom from the need of supporting columns also relieves marine animals of a factor in form-regulation that is one of the most potent and wide-working on land, but which may justly be termed adventitious because it is not inherent in the nature of living matter, nor in an environment essentially favorable. We refer to the fact that animals in the sea have no basic necessity of arranging their limbs as supports — they may or may not carry these on their lower surface. And the contrast in this general respect between land and sea animals is apparent in many other ways.

The high specific gravity of the sea water also exerts another very important, as well as universal influence on the lives of its inhabitants, because coupled with the fact that it is at the same time a nearly perfect fluid, i.e., highly mobile and in constant motion. Through this combination of physical characteristics a mechanism for suspension combined with transportation is constantly at work in all parts of the sea. As a result we see the zone that is permanently habitable extending there to three dimensions, its thickness equaling the extreme depth of the ocean, whereas on land it reaches upwards only to the tops of the highest trees, downward a few

feet into the soil. This allows whole categories of animals and plants, with which science has been much concerned of late, to pass their lives swimming or drifting suspended midway between surface and bottom, an ecologic community that has no true parallel on land, its closest analogy the spiders, insects, and seeds and spores of plants that are borne by the wind.

In this purely mechanical way the problems of transportation and dispersal are solved for multitudes of these drifting creatures (the plankton), assuring the dissemination of whole groups of species in the sea without directive swimming on their own parts. And even many fishes benefit (as species) thereby during their egg and larval stages, or suffer correspondingly if carried to unfavorable regions.

The group-benefits conferred by this involuntary transportation are numerous, even though to the individual it may be fatal. Thus the dissemination of species from the centers of chief production, just mentioned, is assured; in many cases a matter of prime importance for their survival. The problems of reproduction are also vastly simplified thereby, for provided eggs and sperm be produced simultaneously and in sufficient quantity, a means is provided ready-made for bringing the two into contact, without effort on the part of the individuals concerned. And correlated therewith we find that

the development of peculiar mechanisms for this end — the rule among land animals and the higher land plants — is decidedly the exception in the sea, freedom from this necessity being reflected by corresponding morphological simplicity.

The water of the sea, by its constant motion, and by carrying a vast assemblage of living things with it, also provides a much more effective mechanical mechanism for bringing food within the reach of animals that are stationary than ever works on a broad scale on land. And as a wide variety of animals in the sea need merely await what the current brings them, the ability to carry out self-directed locomotion is not the basic necessity there, even for carnivorous animals, that it is on land. In fact, whole categories of flesh-eaters — even eaters of active prey — manage very well in the sea without it, and all gradations are to be seen there from animals that swim or crawl actively at some stage in their life, through such as do so for a time (then becoming stationary as the barnacles and corals) to others that are stationary, or nearly so, from birth to death, such as the stalked crinoids. If density of aggregation or numerical strength in individuals be an index to success in the struggle for existence, the oysters, mussels, and so forth, the deep-sea crinoids, the reef corals, and the sponges find a stationary life highly successful. And this applies even to some ani-

mals of considerable size, such as the giant clams (Tridacna) of the coral reefs.

Thus while most groups of animals in the sea, as on land, have been controlled in their structural evolution by adaptations for locomotion, such as streamlined bodies easy to drive through the water, many others show no effect of this in their form regulation. Such animals teach us, for example, that the possession of lateral limbs, or of the bilateral symmetry with which we are so familiar that we have almost come to look on them as necessary features of a 'higher' animal, is actually not a basic animal necessity at all, but merely adaptation to a particular environment or way of life.

The high specific gravity of water, the fact that it is an aqueous solution, its comparatively constant temperature, the protection that a very thin film of it gives against sunlight, and its incessant motion, combine to make the whole problem of reproduction much simpler for marine, than for terrestrial animals. Eggs need less protection, and the young hatched therefrom are capable of independent existence at an earlier state in development than is the rule on land. So we find that even the most highly organized of the animals of direct marine ancestry (the bony fishes) solve the reproductive problem as a group merely by producing a great many eggs, without any complex arrangements for nursing the

latter, or caring for the young, while larval development is much more usual in the sea than on land. It is true that some fishes (notably the sharks) are viviparous; but judged by the usual criteria this does not seem to have been of any great advantage in group-evolution in the ocean.

The cases so far quoted are enough to show how much more intimately marine organisms (needing no specific protections against the medium in which they live because this is essentially a favorable environment, hence having in most cases developed none) are dependent upon their surroundings, but at the same time far more at the mercy of the latter than are most animals and plants on land. And because responses in structure, in evolution, and in habits, to variations in the environment, are not obscured there by all the variety of protective devices that are developed on land, the sea offers by far the more favorable field for investigations into these subjects.

The peculiar advantages which the oceanic biologist enjoys as contrasted with his terrestrial confrère may, then, be summed up in the one word 'simplicity.' And thanks to this simplicity, we come more easily to grips in the sea with such basic life processes of protoplasm as its incorporation within itself of materials from outside, its growth, and its reproduction.

Similar advantages also apply, in considerable degree, to the investigation of the mental as well as of the physical attributes of marine animals, for, as a corollary to the freedom that these enjoy from some of the most serious difficulties that beset land animals, even the most highly organized of them show a low degree of mentality. Thus there is nothing among the crustaceans comparable to the social systems that some of their insect relatives (ants, bees, termites, and so forth) have elaborated. Nor do any of the fishes of the sea show anything of social organization beyond such rudiments as the tendency of schools to hold together in their wanderings. The animal psychologist thus has at his command in the sea an excellent opportunity to examine what may be called the basic mental processes of a great variety of animals comparatively high in the evolutionary scale, unobscured by the confusing psychic developments that have been stimulated on land by the struggle to survive in spite of harsh surroundings. The problems of large-scale behavior, for instance, as illustrated by the phenomena of schooling, can be studied to best advantage in the sea because they can most clearly be seen there. And the uniformity of the surroundings in which marine animals live makes the sea a far more promising environment than is the land for researches into the stimuli or receptive senses responsible for the so-called 'volun-

tary' migrations. It is still a mystery how fishes and other marine animals are able to direct their long journeys, often in darkness, and always through a medium in which temperature and chemical composition are so nearly uniform over long distances that the most delicate tests are needed to reveal any difference at points many miles apart. The problem here is akin to that of bird-migration, but an even more puzzling one.

The essential difference between the paths of study which may be expected to lead terrestrial and oceanic biologists most directly toward their common but perhaps unattainable goal — solution of the nature of life — may therefore be contrasted as follows. The former studies most profitably the manifold adaptations which animals and plants have evolved to make an unfavorable environment serve their ends: adaptations whether of structure as examined by the morphologist and the taxonomist, of development as seen by the embryologist, of mental processes, or of the internal vital phenomena that fall within the province of the physiologist as discussed in the next chapter. For the oceanic zoölogist or botanist, however, the most productive subjects group around the animal and plant forms, life histories, and so forth, that have developed, free on the one hand from the stimulation and on the other free of the limitations that are imposed on terrestrial

organisms by the necessity of guarding against their surroundings.

Oceanic zoölogy and botany also render invaluable service as handmaidens to other provinces of sea science, because biological phases are inherent in many of the problems of marine geology, physics, chemistry, and so forth. As this interrelationship is emphasized repeatedly in other chapters of this book only a few examples need be quoted here. One thinks perhaps first of the geologist's need for information about the regional abundance, specific distribution, migrations, death-rate, rate of sinking after death, and details of skeletal formation of all the categories of animals and plants whose limy or silicious remains form so large a part of the deep-sea oozes. The pelagic shell-bearing Foraminifera and Radiolaria demand attention in this connection no less than the diatoms which have been the subject of so much investigation of late. Ability correctly to interpret the accumulation of organic oozes today, or in the past, depends upon such knowledge, which applies equally to all the problems that center around the building of reefs from the remains of bottom-dwelling animals — coral reefs, for example — and the origin of shell beaches. The geologist is no less interested in corresponding problems regarding the various mud-eaters that live on the bottom of the sea, because of the destruction (chemical and

mechanical) of existing sediments that they bring about; the rôle which such animals may play in keeping open the lagoons of coral atolls is now under discussion. Knowledge of oceanic biology is equally vital for the palæontologist; he cannot hope correctly to interpret the fossil record in time or space, or the animals of the past, without a much more detailed knowledge than is yet available of the distribution and conditions of life of the animals and plants of the sea, because the great majority of all the species of animals whose fossil remains have yet been found certainly lived in the water, either sea or fresh.

It would be equally futile to attempt any explanation of the cycle of chemical events that is constantly proceeding in the sea without taking into consideration their biologic aspects: in fact it is often impossible to say which of these categories of events is mistress, which handmaiden. Thus it would be idle to discuss the increase and decrease of various chemical solutes in the sea water without knowing something about the decreases and increases in the plant communities that precede or accompany them, because these plants contribute materials to the water on the one hand and on the other hand withdraw other materials from the solution. This applies exactly in the same way to the problems of the lime chemistry, of the alkalinity, and of the gas con-

tent of the water. And as different organic groups are laws unto themselves, the lives of many of them must be examined intimately in these connections.

Students of ocean currents can and have drawn much valuable information as to the sources and directions of flow of different water masses from the animals and plants that the latter carry with them, depending upon the biologist to tell the thermal relationships and probable geographic sources of these natural drift-buoys. And in this case the negative evidence afforded by the absence of particular communities of species may be hardly less instructive than the positive evidence afforded by the presence of certain others.

Oceanic biology also has an important and direct economic bearing discussed in another chapter of this report (page 187).

## 2. Marine Physiology

The general physiologist, whether he works with marine, with terrestrial, or with fresh-water animals, seeks a better understanding of the life processes that are common to all animals and plants, and of the ways in which the basic properties of protoplasm are translated into the complex manifestations of animal and plant life that we see about us. Hence in the words of one contributor, 'Marine physiology is not so much a department of marine

biology as a method of dealing with the whole of that field, in so far as it concerns the properties and relations of living organisms, and parts of living organisms.' Physiologists, therefore, turn to marine organisms in their researches for much the same reasons as do other biologists. And they have the same two specially compelling inducements for so doing; first the abundance, availability, and suitability for experiment of marine animals; second the nature of the sea water environment.

The practical advantages that marine organisms offer this branch of biology call first for emphasis because it is not generally recognized how greatly general physiology has been indebted to them for progress in some of its most basic problems. This applies, in particular, to investigations into such energy relations as involve: (1) temperature, (2) light, (3) gravitation, (4) ionic composition of the medium, for which they afford material on which experimentation can be carried out on a large scale, under conditions where no irreversible changes are induced. Marine animals and plants likewise offer the most favorable opportunity for directly relating the experimental results gained in such fields to the phenomena that actually occur in nature, through study of the physiological adaptations to variations in the sea water environment.

Thus, to quote one example, and perhaps the

most obvious, we know very well that the distribution of marine animals and plants, in fact their whole economy, is largely controlled by temperature. All of them have an optimum range within which they live, with lethal limits above and below. But in many cases the vegetative metabolic activities (expressed as growth) and the reproductive proceed most successfully at different temperatures — witness the growth of the lobster to large size in cold water, but the inability of its larvæ to survive at all except in warm. The question how this temperature control works on the internal activities is now to the fore. Is this a simple matter of difference in the rates of the chemical reactions involved (for certainly the metabolic rates do vary with temperature) or is something more at work? And if well-defined critical temperatures do exist, as has been indicated both by certain field observations and by experiments, how do these influence the distribution, the seasonal activities, and the host of other phenomena that are controlled in greater or less degree by temperature?

Studies of the effect of temperature on the respiratory processes of various marine animals in particular offer a fertile field, and a very attractive one, because this effect is great enough to render tissues that are adapted to the exercise of respiratory functions (i.e., to the transport of oxygen) at one temperature quite worthless in this respect at another, no matter how

much oxygen there may be dissolved in the water. A study of the temperature factor in this relation may to some extent contribute to an understanding of the thermal control of geographical distribution. May this, for example, be one cause of the great differences in thermal requirements between closely related species — or between geographical races of a given species, such as we know to exist among the codfish and the herring, which find their optimum at one temperature in one region, at another temperature in another? In the straits of Belle Isle, for example, the cod prefer and seek much lower temperatures than they do on Nantucket Shoals.

The temperature problem is not only one of the most important in vital economy, but has the added advantage (from the practical standpoint) that this is a convenient factor with which to work, being easily controlled under experimental conditions, while the effects are readily measured.

The specific properties of the respiratory proteins as determinants of the pressure of oxygen gas in the blood are also intriguing in this connection, for the whole question of the oxygen requirements of different animals and of the same animals at different temperatures is little understood. What, for instance, is the physiologic difference between the blood of active fishes and mollusks, such as mackerel and squid, and that of their more sluggish relatives,

and between the tissues that perform respiration among animals with different thermal optima that have no blood, but take in oxygen directly through their epithelial surfaces — the cœlenterates, for example? Very little, too, is known about the respiration of the marine mammals; sundry interesting problems spring to mind in this connection.

The basic nature of the respiratory pigments — any pigment, for that matter — has hardly been touched as yet from the standpoint of specific differences within a given group of animals, or of the qualities with respect to oxygen of the compounds, that in lower animals are analogous to hæmoglobin in the higher. It is not unreasonable to hope that knowledge, here, may lead to better understanding of the blood physiology of mammals, and so of man. Crustacea, worms, and fishes, among marine animals, lend themselves more readily to investigation in this connection than do any land animals. And respiratory pigments are only one of a great number of substances that cry for study from this point of view. In fact, the whole relationship between chemical composition and systematic relationships among different groups of animals and plants is still a practically virgin field; one offering fertile possibilities to the marine physiologist.

Various other comparative studies which can most favorably be carried out on sea animals, might also

prove of assistance to the human physiologist in his attempts to interpret the phenomena he has to deal with. Especially interesting in this field is the occurrence in mammalian blood of salts in proportion similar to sea water, with the contrasting fact that while the body fluids of sea fishes are nearly the same as sea water in this respect, they are never precisely so. The whole question of the physiological significance of the different salts is, in fact, a most important one, to explain which no satisfactory theoretic basis has yet been arrived at. Here new lines of attack are opened by recent advances in the physical-chemistry of salt solutions, for which marine animals, because of their simplicity, are the most promising subjects.

We have selected these particular fields of study for mention as illustrations of the desirability of applying the methods now practiced in the investigations of the respiratory, circulatory, and blood physiology of man to the comparative physiology of marine animals to a much greater extent than has yet been attempted. An eminent physiologist, indeed, gives it as his opinion that this is one of the great scientific opportunities of the coming half-century; and that voyages of well-equipped expeditions, making use of experimental methods of this kind, promise to put the natural history of the sea on a new level.

In like manner, the key to the riddle of the secretion of gas, over which there has been much controversy in the field of pulmonary respiration, may well be found in the physiology of the swim bladder of fishes, about which little is yet known with certainty. Many questions of nutrition, such as might well be attacked in marine animals, would also find application in the physiology of the higher animals — so, too, the manner of excretion of waste products by the animal groups that have no special organs for that purpose. This, for example, would include the intra-cellular pigments and the crystalline secretions of medusæ.

Calcium metabolism, as reflected by the deposition of lime salts in bones, is another field on which studies in marine physiology might throw much light. Thus the relation between ocean temperature, the occurrence of lime-secreting animals, and the amount of lime they secrete, suggests the importance of investigations into the rôle played in calcium secretion by the effect that other electrolytes may have on the solubility of calcium carbonate.

Fertile subjects in the whole field of the physiology of light are to be found among the great variety of marine animals of widely divergent groups that live normally in regions of very dim light, or of darkness, and so may not have developed an adaptive physiologic protection against the lethal or other meta-

bolic effects of the whole of the sun's spectrum, or of any part of the latter. This in turn, leads to the very interesting problem of luminescence, so highly developed among marine animals. Furthermore the light tropisms of species attuned to a higher degree of illumination, are more easily studied on marine than on land animals. And this applies even more strongly to geotropism.

Many other significant matters might also be approached through the physiology of the animals that live in the depths of the oceans, under conditions very different from those prevailing near the surface, if they could be controlled in the laboratory, which has never been possible so far.

The activities of individual marine organisms, especially those of the littoral zone, likewise provide the widest variety of subjects.

Very attractive opportunities are open for researches concerning the many shoal-water animals that are of commercial importance, the sane conservation of which depends upon knowledge of life history. And the incentive to put such matters on a sound basis is strong, for much of the work so far attempted in this field has failed to command full confidence, both because of the technical procedure employed, and because of the character of the result sought.

Physiology, furthermore, is concerned, not only

with the activities of individual animals or plants, both as such, and as they illuminate specific problems, but also with the inter-connected activities, and ecology in general, of different organic groups. The sea offers the readiest subjects for such investigations, and those likely to provide results of the widest significance.

The investigation of abstract problems, in all these fields, requires, in the first place, the selection of the type of organism that seems the most likely to prove suitable for the specific question in hand. For this reason, alone, if for no other, the marine biological laboratories should expand their functions as foci for physiological research, since by contrast with the faunal and floral equipment of the land, or of fresh waters, the sea is extremely rich, both as to individual numbers and as to variety of types. Here, for example, we think of the abundance and diversity of luminous forms in the sea contrasted with their paucity on land and practical absence in fresh water; of the wide range of colonial animals; of the expression of types of symmetry other than the bilateral; and of various forms of appendages, and so forth, among the marine population. And when we turn to cellular physiology, we find that the large size, abundance, constancy of physiological condition, and simple cultural requirements of such free-living cells as the eggs of sea

urchins and starfish, among others, make them incomparable material. This is true whether surface processes or internal colloidal phenomena be in question, and whether studied by temperature variations, by chemical means, or by microdissection. It was, therefore, no accident that general physiology in America arose at the Marine Biological Laboratory at Woods Hole, or that the pioneer studies in artificial parthenogenesis, of balanced solutions, and so forth, were carried on at seaside laboratories, rather than inland.

The most impelling lodestone to draw physiologists to the sea (just as in the case of the zoölogist or botanist) is, however, the physical and chemical nature of the salt water itself. The essential suitability of the latter as a home for protoplasm has often been emphasized of late, and justly; for though (as one contributor points out) we ought to regard sea water as a specific environment because salt lakes, very different in chemical composition, also support life, the sea (if judged by the variety of plant and animal forms that have developed there) is far the more suitable medium. And while this does not necessarily mean that it is inherent in living matter to be best fitted to exist in sea water or in some solution very similar to the latter, this certainly applies as a general rule, under conditions as they actually exist. Furthermore, it is the particular nature of the

sea water alone that makes life, as we know it, possible anywhere in the sea outside a very narrow coastal strip. Were sea water not nearly as heavy as protoplasm (thus making flotation easy) and did it not carry in solution a variety of chemical compounds usable by plants as food, the abundant plant life of the seas could not exist at all except close to the lands: without plants there could be no animals except there, so that the whole oceanic basin would be a desert.

Sea water, furthermore, is not only a favorable, but a complete environment (for it contains in solution all the known elements not only in simple inorganic, but some also in organic combination), having properties that can be precisely defined, measured, and altered at will under controlled laboratory conditions, i.e., temperature, total salt content, concentrations of different solutes, ionic dissociations, osmotic pressure, and so forth.

Marine physiology therefore centers around sea water as an environment for life. And the most promising approach to all those interactions between protoplasm and its surroundings, by which life is sustained and which set all living matter apart from all non-living, is through quantitative study of the interchange between the cell and this environment. We need only refer to the very suggestive work that has been done of late on the selective permeability

of cell membranes and on the accumulation of ions. None of these interactions can be directly traced in the air, nor could be in fresh water unless the latter carried substances of some sort in solution.

But our present knowledge of the physical and chemical characteristics of sea water is so imperfect that we still lack the just physiological interpretation of what it really is, that is needed as the rational starting point in many lines of investigation. Before the physiologist can assay the rôles that organisms of various kinds play in the ocean equilibrium, and *vice versa*, he, or his chemical colleague, must measure, quantitatively, the periodic alterations of significant chemical constituents that take place in the sea water. Only now do we begin to understand the progressions of nutritive substances, and the regulation of their levels of concentration, as related on the one hand to depth, to distance from land, to seasonal periodicities, and so forth, and on the other, to organic production and destruction.

The question by what mechanism the cell is able to select out of the water those rare substances that, as it now seems, are of vital importance, opens the whole problem of the specific affinity of different cells for particular chemicals that forms the basis for all the structures that protoplasm manufactures. We might mention the secretion by diatoms of silica (an element relatively rare in sea water) in such

great quantity that at times they may almost exhaust the water of it; the ability of seaweeds to draw iodine and potassium from the surrounding water so much more efficiently than man can, that until other sources for these substances were discovered it was far more economical to obtain them from the ash of seaweeds than it would have been to concentrate them direct from the water by any method yet perfected or likely to be developed: the ability of certain unicellular animals (Radiolaria) to build their shells of strontia, a substance so rare in the water that only recently have analyses revealed its presence there. If any seaweed made equal use of gold, the commercial extraction of the latter from sea water (on the average there are about five milligrams gold per cubic meter of water) would not be the will-o'-the-wisp it has actually proved. A more familiar example of the ability of the living cell to select particular substances from the outside is the secretion of limy shells by a great variety of plants and animals, an ability responsible for vast deposits of calcareous sediments, of limestone rock, and of the modern coral reefs. The question of the draft made by different vegetable cells of specific solutes for their nourishment, as of nitrates and of phosphates by diatoms: or of the same solutes in different proportion, is now under investigation at many hands.

The degree of permeability of membranes for dif-

ferent solutions also holds the key to the riddle whether marine animals can feed directly on the organic substances in solution in the water, before these have been reduced to their constituent nitrates, carbonates, etc. The theory that they so do (the so-called 'Putter's theory') has been much discussed, but is still open.

Certain of the gross phenomena associated with such withdrawals of materials from the water of the sea by animals and plants are familiar enough; the formation of reefs for example, or local swarmings of diatoms. But little is yet known of the factors that control them. Why is it, for example, that organisms take out more lime in high temperatures and shoal water, more silica in low temperatures and in the deeps? The chemical reactions that have been proposed to account for such differences do not wholly explain them, and the vital mechanism back of this selectivity (perhaps the most fundamental of all the peculiarities of living substance) is still a mystery to us. Its solution (akin to the solution of life itself) may never be reached. But certainly its manifestations can be most directly studied in the sea, where, for example, we often find one group of unicellular plants thriving in water that some other group had already rendered barren for itself by denuding it of the chemicals on which it subsisted, and where the whole range of phenomena associated

with the specific affinity of these lowly organisms for particular substances is effected on a vast scale by the simplest organisms.

All of this converges in turn upon the underlying problem of the basis for the group and specific differences in protoplasm: differences that are reflected in all the diversity of life that has existed on our planet.

Studies in this field have also a directly human interest, for through them there seems hope of learning how it is that our own body cells select one substance or another from our own food *via* the blood stream, a question about which we are still almost wholly in the dark.

As a final thought on a somewhat different plane, added to this report by one of its contributors, 'one of the present duties of physiology is the revivification and modernization of general natural history. Long experience with fragmentary investigations of the sea has at least made it clear that this association of interests is desirable, and that life in the sea is one of its most fruitful fields. Perhaps this is due to the fact that a certain mental humility often follows contact with the complexity and immensity of the ocean.'

### 3. Marine Bacteriology

Present-day preoccupation with medical science makes us prone to think first of bacteriology in its re-

lation to human diseases. The problem of disease, however, seems not to be of great moment in the sea. Thus, while fishes (and no doubt other marine animals) do suffer from a variety of bacterial infections, and while the human aspects of bacteriology do reach into the sea to some extent, as when typhoid — and other disease-bacteria, coming from the land, gain foothold in the bodies of oysters, clams, or other shellfish, most of the pathogenic bacteria (though capable of living and multiplying in sea water with added nutrients) have been found to succumb rapidly in normal sea water. By and large, the disease-bacteria of man and of the higher animals do not thrive in the open ocean.

The problems of marine bacteriology that we wish to emphasize here are more akin to those of soil bacteriology, for they center around the rôles that bacteria play in keeping in motion the cycle of matter through its organic and inorganic stages in the sea. If we write less confidently on this subject than we have on oceanic zoölogy (page 127), or on marine physiology (page 152), it is because our knowledge of bacteria in the sea is still woefully scant. But such glimpses as have been gained of their activities there are enough to show that these must be assayed before we can hope to understand the maintenance of organic fertility in the oceans.

The simplest task of marine bacteriology is per-

haps to trace the direct service these lowly and minute organisms render to the larger in providing the latter with proteid food. That protozoans do feed on bacteria in the sea is established. In fact, recent studies suggest that in this passive way the bacteria that thrive on the organic débris accumulating in shoal waters, and the protozoa that prey upon these bacteria, are essential links in the food-chain of higher animals in coastal waters, where the echinoderms, mollusks, and others that feed on detritus gain their nourishment less from the latter direct than from bacteria and protozoa eaten at the same time.

This question is a quantitative one; the answer depends on the numerical distribution of bacteria regionally and with depth. In general, the sea water is known to be much richer in bacteria near shore, where land drainage maintains a state more fertile for them, than out in the open ocean; especially is this true of the forms that subsist on the excreta of animals. But viable bacteria have also been found to exist far out at sea, away from coasts, increasing in number down to a certain depth, while many of them at least are killed by strong sunlight. It is certain, too, that bacteria are abundant in many of the muds not only in moderate but even in considerable depths. Do these serve the whole category of mud-eaters as food on the slopes of the continents, and

should bacteria be regarded as the primordial meat supply of that belt of the ocean; or is their rôle in this respect important only locally? We know nothing of their relative abundance at great depths, or in the abyssal mud, except that there, too, bacteria do exist.

In attempting to interpret the food-cycle in the sea, bacteriologists must also take into account the possibility that among the bacteria devoured by protozoa and perhaps by the mud-feeders generally, there are enough of the sorts that can change carbon dioxide to organic carbon without sunlight, to form an important primary food for some animals, so short-circuiting the line from animal to plant and back again to animal, by freeing the latter from dependence upon the photosynthetic plants. The nitrifying bacteria discussed below fall in this autotrophic category, being able to obtain all their vital requirements from simple chemical compounds, such as ammonia, nitrous acid, and carbon dioxide. And there are other categories of bacteria similarly chemosynthetic; for example, the methane, hydrogen, and carbon monoxide groups. Beyond the fact that the nitrifiers and perhaps some of the others do exist in the sea, we have as yet no knowledge as to how important they are as sources of primary foodstuffs for animals. It is with regard to the inhabitants of the abyss where no ordinary plants can exist that this question is the most intriguing.

More generally significant than the simple relationship of bacteria to marine animals as prey for the latter, is their relationship to the circulation of nitrogen through its organic and inorganic phases in the sea. It has long been known that the sea water is nearly saturated with nitrogen gas at all times and places. But none of the ordinary marine plants, so far as we know (and certainly none of the marine animals) can use nitrogen in this elemental form, though every one of them requires nitrogenous nutriment. For the animals, this food comes in the long run from the plants; and all marine plants (except certain bacteria) are believed to depend for their existence on the presence of certain salts of nitrogen (chiefly nitrates) in solution in the sea water. The fact that the latter contains these salts reflects the activity of certain groups of bacteria, either *in situ*, or on land. These include the putrefactive bacteria, the nitrifiers, and the nitrogen fixers. Until the complex proteids and carbohydrates contained in the bodies of dead organisms are reduced to simple compounds they can be used only by carnivorous animals, by fungi and by bacteria; not by the photosynthetic plants.

Great amounts of nitrogen, it is true, in combinations directly usable by the latter, are contributed to the sea by discharges of river waters, carrying with them the drainage from the land, also from

air; but a greater potential source is the decomposition by bacteria of the carcasses of marine animals and plants within the sea. Bacteria of decay seem to be as ubiquitous in the sea as they are on the land; witness the rapidity with which carcasses rot in the water at moderately high temperatures. And not only can they usually be isolated from decaying fish, but certain of them are normal intestinal inhabitants of haddock, no doubt of other species of fish. As yet, however, we have no precise information as to how temperature, darkness, pressure, and the supply of available oxygen affect the activities of this putrefactive group in the deeps where much of this decomposition takes place. And this question looms large in oceanic economy because the rapidity with which carcasses break down (one of the two factors that in the end control the fertility of the sea) controls the state in which organic detritus reaches the sea floor in its descent from the upper layers, to maintain the reserve supply of dissolved nutrients, and so forth, in the deeper water.

Evidence at present available, especially the fact that mass production of diatoms reduces the supply of nitrates in the water, but not the supply of ammonia, indicates that marine plants as a group cannot utilize the end-product of putrefaction (ammonia) direct, but only after it has been transformed, by oxidation and combination with bases, into ni-

trates or nitrites. And so far as is known, this transformation proceeds only through the agency of certain groups of bacteria, the so-called 'nitrifiers.'

The chemical reactions that bacteria of this group bring about in sea water, under controlled conditions in the laboratory, are known. And their presence in bottom muds in various localities, both in high and in low latitudes, has been established by the fact that inoculation with such muds of salt water containing ammonia in solution results in the formation of nitrates. It has been proven by similar experiments that nitrifiers also exist in the water close to the bottom: likewise in surface water near land, but only in situations where there is much silt and detritus in suspension, suggesting that the bacteria in question are associated with the latter. But so far as I am aware, no direct evidence has been obtained that nitrifiers exist in the waters of the open sea away from the coast and from the bottom, though tests have been made to that end. Available experimental evidence therefore suggests that in the sea the alteration of ammonia into nitrates takes place on a significant scale only close to the shoreline and on the sea floor, not at all in the surface waters or in the mid-strata of the open sea. This, if correct, locates the chief zone of regeneration for nitrates by bacterial action as coinciding with the zone of regeneration for phosphates in shoal mar-

ginal seas, but as lying at a considerably greater depth in the ocean basins. But the correctness or reverse of this view remains to be established.

Our only present indication as to the scale on which the nitrifiers actually work in the sea is the rate and regularity with which the supply of nitrates and nitrites is regenerated in the surface waters, after it has been exhausted by abundant growths of planktonic plants. And to illustrate how small a basis for broad deduction is yet afforded by such data, I need only add that pertinent observations have so far been confined to short series of observations at a few localities in shoal water, and that owing to technical difficulties, few (if any) of the analyses for nitrates and nitrites that have yet been made have been entirely satisfactory.

We have still to learn whether we can interpret the responses of the nitrifiers (in rate of multiplication and efficiency of action) to variations in temperature, light, oxygen, and state of the ammonia and other organic derivatives present, by analogy with their activities on land: they may follow different laws in the sea. Definite information as to their relative importance in muds under deep and under shoal water is so far lacking. But these questions (about which different views are held, more on the basis of deduction than of observation) must be answered before we can assess the relative importance

of different depth zones of the sea bottom as sources for the regeneration of the salts of nitrogen. And this whole matter is especially pertinent at present, when the vital activities of planktonic plants are receiving so much scientific attention, because correct interpretation of the variations in abundance and in season of multiplication of the latter depends on a knowledge of the relative importance of nitrifying bacteria within the sea, of land wash, and of nitric acid from the air, as the agencies that maintain the stock of nitrates in the superficial stratum of water, or renew it there when temporarily exhausted. This applies particularly over the continental shelves, where planktonic plants reach their maximum abundance.

The possibility that the so-called 'nitrogen-fixers' may also add significant amounts of nitrogen salts to the sea water, in some regions, in forms directly usable by ordinary plants, must also be taken into account.

Bacteria of sorts that have long been known to assimilate atmospheric nitrogen in the soil, if they are also supplied with non-nitrogenous sources of energy, and to fix it in compounds usable by plants, have also been found widespread in the sea in shoal water, at localities as far apart as the Baltic, the North Sea, and the Indian Ocean: also in the plankton. Organic carbon going into solution in the

water from the breakdown of the bodies of defunct animals and plants supplies them with the chemical energy that they require to carry on nitrogen-fixation. There is experimental evidence that they are able to fix the nitrogen gas with which sea water is saturated, just as they do the atmospheric nitrogen in the soil on land. And so far as it goes, any conversion that they effect of nitrogen gas to nitrates in the water must be of direct importance in marine economy, by making a nitrogen supply available for marine plants which cannot use it in the gaseous state. But we have yet to learn how to assay, in quantitative terms, the frequency with which such bacteria have been found associated with seaweeds in shoal waters (where the concentrations of life are the greatest); neither have we any direct information as to whether they ever operate on a significant scale there, or in any other part of the sea. In fact, there is no general agreement, yet, as to the quantitative importance on land of such of the nitrogen-fixers as live free in the soil; and it is to this group that the marine nitrogen-fixers belong that have so far been found in the sea. Neither is it known whether there is anything in the sea comparable to the symbiosis that exists on land between other nitrogen-fixers and certain leguminous plants. Final solution of the general problem of whether the nitrogen-fixation by bacteria in the ocean is anything more than a

minor event would be one of the welcome gifts that marine bacteriologists could offer to oceanic biology.

Before any sound explanation of the nitrate and nitrite cycle in the sea can be arrived at, the activities of the denitrifiers there must also be worked out quantitatively and empirically as well as qualitatively and by deduction, for these (as far as they operate at all in the sea) tend to denude the water of nitrates by breaking these compounds down to ammonia, or even to nitrogen and its oxides, thus putting them out of reach for the photosynthetic plants.

It has long been known that denitrifiers do exist in the sea water, and much discussion has centered around their supposed activities there. But, lacking quantitative information, we have no clear conception of the scale on which they actually effect such losses in the open ocean, both because of our ignorance of their abundance in its different parts, and (more important) because the factors that govern their denitrifying activities in the sea water are not yet understood. It has long, and generally, been believed that bacteria of this group operate more efficiently at high temperatures than at low. Arguing from this supposed fact it has often been suggested that the scarcity of nitrates actually recorded in the tropics, as contrasted to colder waters, reflects greater activity of these bacteria in warm seas; consequently, that the regional differences in the losses

of nitrogen that they cause are responsible for the supposed general paucity of phytoplankton in the tropics as compared with higher latitudes.

But this theory, like many another that has been set up in oceanic biology, is based on only one factor in the environment, when actually others may be more important; and on a numerical abundance of the organisms concerned which, while easily maintained in the laboratory, may never exist in the open sea. Recent experiments, for example, have suggested that while temperature controls the rate of activity of the denitrifiers, they actually attack nitrates only when oxygen is deficient. This would point to great possible losses of available nitrogen, by their activities, in the bottoms of certain enclosed basins, in the mud generally, and wherever oxygen is relatively scarce in the mid-strata of the oceans, but to little or no denitrifying activity on their part in the surface layers which are nearly saturated with oxygen. If, however, these bacteria are active in the mid-depths, the results of their cumulative work there may lead to a great loss of nitrogen that must be made up in some other way, because much of the decomposition of dead carcasses, sifting down from above, takes place at this level. What is needed here is empiric determination of what actually does take place, more than theoretic discussion of what might happen.

How active the denitrifiers are in the mud is also a live question, because the sediments on the sea floor, in deep water as well as in shoal, contain considerable quantities of organic nitrogenous compounds, which, so long as they continue in chemical combinations subject to the action of putrefactive and nitrifying bacteria, are a potential food supply that may be brought to the plants in the upper waters by vertical currents. In the Gulf of Maine, for instance, the bottom muds contain on an average about as much nitrogen as good garden soil, much of which is probably distributed throughout the water at the seasons when vertical circulation is most active. It may be assumed that a scarcity of oxygen everywhere in the mud below the superficial skim sets the stage for the destructive effect of the denitrifiers there, unless the temperature be too low for them. But we are still entirely in the dark as to how effectively they do act in the mud, i.e., what rôle they play in preventing the accumulation of nitrates in the submarine deposits, for while these salts are extremely soluble in the sea water, organic particles tend to be trapped in the mud wherever sedimentation is rapid, and thereby to be protected from the action of the water. Any nitrogen locked up in this way would be a dead loss to the oceanic complex until in some way brought back again into circulation.

It is because animal life in the modern ocean

depends vitally on the presence of photosynthetic plants for its ultimate food supply that we have so far stressed the general problems that center around the rôles of bacteria in keeping the sea water fertile for these plants by maintaining the stock of dissolved nitrates and nitrites, or by replenishing the water with these substances when active multiplications of diatoms, and so forth, have locally reduced the supply below the minimum concentration necessary for the nourishment of marine plants.

We have yet to learn whether bacteria of fermentation, or any other fermenting organisms such as yeasts, are abundant enough in the open sea or in the sea bottom (if they exist there at all) to play any broad scale part there in the cycle of carbon, as bacteria certainly do in the cycle of nitrogen. Whether the carbohydrates contained in the carcasses of animals and plants are devoured by scavengers, or whether they simply disintegrate in the water to their ultimate breakdown, their end states are carbon dioxide and water. In the second case it is possible that fermenting bacteria, and so forth, play a significant part in the process. But lacking direct experimental evidence it must not be assumed that this is necessarily so, because it is also possible that enzymes formed within the bodies of animals and plants in life in their normal metabolism are the agents principally responsible for

the breakdown of their organic carbon-compounds, after death has destroyed their immunity to self-digestion.

We also need to know what part bacteria play in breaking down the more refractory organic substances that would accumulate on the bottom of the sea if there were not some mechanism to disintegrate them and to bring them into solution in the water. Specifically, what quantitative rôle do bacteria play in the sea, in the destruction of the agar from the stalks and fronds of seaweeds that is constantly taking place under water — a substance resistant to most bacteria? Bacteria of the sorts that do attack agar have recently been found in brackish and in salt water. But, so far, it has been only in the tropics that their presence in such situations has been established, whereas it is in higher latitudes (and lower temperatures) that the great concentrations of ordinary seaweeds exist, and the great overturn of agar and of similar hemicelluloses takes place. Thus it still remains an open question how far the annual disintegration of the millions of tons of kelp, and so forth, results from bacterial activity, or how far it simply reflects the solvent action of the sea water itself. We face this same problem with regard to the destruction of the chitin in the shells of dead crabs, shrimps, and other crustaceans, and of the oil from diatoms and copepods.

Bacteria certainly play other important rôles, which, as yet, we only glimpse, in the chemical changes following the alteration and decomposition of organic matter that takes place in the deepest water and in the bottom sediments. Here we think at once of the forms that reduce sulphates in the absence of oxygen to sulphides in the black muds of shoal waters, especially in enclosed basins with little circulation. Bacteria, too, are indirectly responsible for the accumulation of sulphurated hydrogen in the deeps of the Black Sea and of certain fjords. We greatly desire more detailed bacterio-chemical studies of the deep water of other such basins, e.g., of the Sulu Sea. The activity of these same groups needs to be studied in the open ocean, where, because of the active circulation of the water, their effects are not so apparent. We know almost nothing about the activities of bacteria in the abyssal muds; a question especially important in connection with the deposition of iron, and from other points of view, as well.

It is still a live problem whether, or to what degree (if at all) bacteria cause calcium precipitation in the sea. This question (as is usually the case) cannot be answered simply by finding out (as has been done) that certain of them can precipitate lime out of sea water under special conditions in the laboratory; we must also learn whether they are associated with the mass precipitations in the sea in significant numbers;

also whether there is sufficient supply of nutrients in these situations to support their growth, and (by studies of physico-chemical relationships in the water) what chemical changes such precipitation involves. The necessity for uniting several disciplines in this case illustrates how broad a view must be taken of biophysical and biochemical problems as a whole in the ocean.

A few more problems that have a general bearing both on bacteriology *per se* and on the science of the ocean, may be mentioned. What rôle is played, for instance, by the luminous bacteria, whether as saprophytes or as normally symbiontic with animals and plants? Do these bacteria exist at abyssal depths? If so, are they sufficiently abundant for their luminescence to be important in the vital economy of deep-sea animals? Do they, perhaps, help to make vision possible for the large-eyed benthonic fishes of the abyss, most of which are non-luminous themselves?

The marine anærobes have received scant attention. Here the recent discovery that $CO_2$ tension rather than oxygen tension is the requirement that distinguishes them from ærobes, emphasizes the necessity for further information as to chemical conditions in the water.

A bacteriophage has also been reported in the sea by French oceanographers. How generally this

principle (destructive to bacteria) is distributed through the oceans, and how effectively, if at all, it combats the manifold activities of marine bacteria remains to be learned.

Microörganisms other than bacteria have also been found in the ocean and may have a quantitative importance in the chemical processes that have been enumerated comparable to that of the bacteria proper, a relationship that has been well established in the case of soil microbiology. The Actinomyces may be cited as a group that are worthy of attention as are the bacteria themselves: this also applies to the yeasts.

The answers to the principal questions that the oceanographer may properly ask of the bacteriologist are not as directly available as mere enumeration of them might suggest; in this particular field, perhaps more than in any other division of sea science at present, it seems certain that no great headway can be made until technique is perfected. No one instrument will solve the problem of bacteriological sampling in the sea. For purposes of enumeration the sample must be large: to concentrate it prior to microscopic enumeration is often difficult. The sampling of water for culture work, when small volumes suffice, presents few obstacles, but it is otherwise with the sampling of mud, for in this case it is necessary to recover an undisturbed specimen so

that the sample can be examined serially, commencing for example with the top millimeter, unmixed with lower layers and unwashed by superposed water on the ascent. We have also to learn what modifications of the routine media, or of those favorable for soil organisms, will give the maximum counts of bacteria from a given sample of ocean water. We shall not be able to assay the significance that should be attached to the physiological activity of marine bacteria until we are able to grow most of the organisms that can be found in the water. And, in general, we must emphasize that random procedure, and approximate technique can never serve as the basis for evaluating the general share of bacteria in the economy of the sea.

# CHAPTER VI

## ECONOMIC VALUE OF OCEANOGRAPHIC INVESTIGATIONS

THERE is hardly an aspect of oceanography but affects one or another phase of modern civilization; and naturally so, for this science is concerned with the physical and biological economy of some seventy-one per cent of the earth's surface.

When oceanography is considered from the severely practical standpoint of human economics, a distinction must be drawn between the study of such oceanic phenomena as exercise a basic control over the habitability of the lands, and of such others as man can turn to his benefit by his own efforts, but which will neither serve nor harm him otherwise. The first category includes the general influence that the oceans exercise on the climates of the continents. The second covers all the ways in which man can draw raw material for his use from the sea; also it covers the knowledge he needs to make the latter a safe highway for his commerce. It is with this second category that we are now concerned.

Food and safe navigation are now, as they have always been, man's most urgent demands from the sea. Therefore, the lines of oceanographic study from which the most direct economic advantages

may be hoped at present are those having to do: (1) with the biology of the animals that support the commercial fisheries; (2) with the various events in the sea that affect navigation, and with the contour of the bottom from this same standpoint. In fact, it has only been as knowledge has increased with the progress of civilization, that greater and greater utilization of the biologic resources of sea (fisheries) has become possible, and that navigation has been made reasonably safe. The study of the characteristics of coastwise currents, as affecting harbor construction, and so forth, along sandy shores, and a more detailed exploration of the contour of the bottom to make easier and cheaper the construction of submarine cables may conveniently be discussed in connection with the navigational aspect, the technical procedure being similar. Investigation as to whether the relationship that the temperature of the sea water and its circulation bears to the temperature, pressure, and circulation of the overlying air, can be made to afford a basis for long-range forecasts of climatic variations, is also an economic problem now to the fore.

Other subjects less promising of immediate commercial advantage, but which may eventually lead to useful developments, include: (1) chemical studies to test the possibility of profitably extracting from the total sea salt, that has so long been an important

object of commerce, or from sea water direct, the many other substances that it contains beside sodium chloride; and (2) attempts to derive power from tides, waves, thermal contrasts, and so forth. At present the problems involved under these headings are more technologic and economic than oceanographic; nor is it possible to foresee how rapidly — if at all — the exploitation of the sea will develop in these directions. The following discussion of the economic value of sea science is therefore limited to the marine fisheries, to circulation and depth of water as affecting navigation and the other matters mentioned above, and to oceanography as a possible adjunct to long range weather forecasting.

## 1. The Sea Fisheries

Much has been written of late about the total productivity of the sea, and the fact that this may be greater (per unit of area) than that of the land has been emphasized repeatedly. But under present conditions of civilization the great majority of the species of marine animals and of marine plants must be left out of account as promising sources of human food. And even if economic pressure should finally drive the white races to turn to such unfamiliar sources as sea urchins, holothurians, or seaweeds, for important additions to the food supply — all of these are eaten, more or less, in various parts of the

world — it is safe to predict that the land will always be the chief source for human food, at least for as long a period as it is worth while to be concerned with the future course of events.

It is not necessary, however, to credit the sea with any fanciful possibilities in order to bring out the great importance that the fisheries have always played in human economy. Each year man draws an enormous amount of human and stock food from fishes, crustaceans, mollusks, even from seaweeds; also oil from fish as well as from the blubber of seals and whales; glue and fertilizer from fish scrap; and pearl essence from scales; while the manufacture of leather from shark skin is an industry that may reach considerable proportions if a dependable supply of raw material can be made available. The increasing pressure of population upon agriculture on the land makes the expansion and proper conservation of the harvest of the sea every year a more pressing problem, for the demand for more complete utilization of the resources of the fisheries grows more insistent.

We must assume that this pressure, not only on the resources of the Atlantic, but of the Pacific and Indian Oceans as well, will continue and become more intense. For as population multiplies in the countries bordering on those seas, fisheries will correspondingly advance in efficiency of method, and

an intensity of effort, extending at the same time farther and farther afield to regions where the supply has hardly been tapped as yet.

The following statistics may make the economic value of these products of marine animals and plants more concrete. The sea food, for example, taken in an average year within the confines of the Gulf of Maine (comprising the 200-mile sector between Cape Cod and the Scotian Banks) amounts to about 500,000,000 pounds, or enough to give one hundred pounds, more or less, to every inhabitant of the New England States and of those parts of the Maritime Provinces of Canada that border on this sector of the sea. The fisheries of California on the opposite side of the continent yield about 600,000,000 pounds annually. The annual catch of food fishes off the Atlantic coast of the United States is 700,000,000 to 800,000,000 pounds; of fish for oil and fertilizer about half as great: of shellfish (without the shells) more than 140,000,000 pounds. The combined yield of the fisheries of the United States and of Canada is about 3,300,000,000 pounds annually, worth more than $100,000,000 to the fishermen. The catch of cod alone in the western North Atlantic has averaged annually about 1,100,000,000 pounds for the past forty years. As long ago as 1912 the value of the fisheries of the countries of northwestern Europe was about $135,000,000. The annual world yield of

aquatic products (most of it marine) is more than 27,000,000,000 pounds in weight, and more than $1,000,000,000 in value. Surely, an industry of this magnitude deserves the most intelligent management possible.

Correct management in this case must be predetermined by the fact that most of this vast supply (chiefly utilized as human food, but also including important by-products), is a truly natural resource, as contrasted with the yield of agriculture on land; man has nothing whatever to do with its production or support, but merely takes a part of the wild crop that the pastures of the sea nourish. It is true that numbers (that seem enormous by any absolute standard) of sea fishes have been and are artificially propagated and returned to the sea every year, but it is doubtful if these efforts have had any appreciable effect on the stock of any important commercial marine species; this is recurred to below (page 201). And while shellfish are cultivated to some extent, this industry is in its infancy. The sea fisheries are thus more nearly on a par with forestry than with agriculture; and the methods of management, to be successful, must conform more nearly to the procedure followed in a forest where natural reproduction is depended upon to maintain the supply, than to the management of any cultivated crop.

We see a measure of the productivity of the sea

pastures in the fact that while no wild crop on land, plant or animal, can long withstand intensive harvesting unless replaced by human effort, men still fish for cod on the Grand Banks as successfully as did the fishermen who first ventured to the shores of Newfoundland for that purpose.

Vast, however, though the supply of fish and shellfish be, fishermen have long appreciated that the stock of fishes in the sea is not unlimited; the rapid disappearance of whales almost to the point of extinction, when they are hard-hunted, is a warning. And greatly though the extent of the oceans exceeds that of the lands, all the great fisheries (except for whales) are confined to a comparatively narrow belt, along the shelves and slopes of the continents; also to comparatively shoal water. On the American side of the North Atlantic, for example, the outermost of the productive fishing grounds lie only about 250 miles out from the land (off the shores of Newfoundland). And the grounds or banks on which the important commercial species are plentiful enough to support profitable fisheries occupy only a fraction of the area between the coastline and the continental slope that marks their offshore boundary. In the deeps outside the latter no great fishery has ever been developed, nor is there any hope of such. The case is similar on the opposite side of the North Atlantic. In fact, the whole basin

of the North Atlantic outside the 1000-meter contour is barren from the fisheries standpoint. Nor is this barrenness due to distance from land or to the difficulty of fishing at great depths, but to the fact that, in spite of the long list of fish species that people the ocean basins at all depths, these are few in individuals compared to the population of the inshore grounds, while most of the oceanic species are small.

Consequently, there is no reason to hope that any true deep-sea fish will ever support an important fishery, or that great fisheries will ever be developed in the North Atlantic much farther out from the land than at present.

In the South Atlantic, Pacific, and Indian Oceans a still smaller part of the total area offers commercial fishing possibilities than in the North Atlantic. In short, only a small fraction of the total area of the sea supports practically all the fish species (and individuals) from which mass production of human food, or of other useful products, can be hoped. The whale fishery alone leads out into the high seas far from land, and no increase in the yield can be expected from that source: on the contrary, how to maintain the stock of whales in the face of even a moderate kill, not how to utilize them more fully, is now the crying problem.

The past quarter-century has seen a rapid increase in the intensity of fishing in the North At-

lantic, in response to the increasing demand for fish, favored by more effective methods of harvesting the catch, by improved transportation, and by better systematized marketing. For all these reasons the demand for sea food and for the by-products of the fisheries (oil, soap, fertilizer, leather, and so forth) will continue to increase; to meet this increasing demand the stock of herring, cod, haddock, halibut, lobsters, and the rest will be subjected to a more and more intensive drain. The intensity of the British steam trawl fishery, for example, increased by 11 per cent from 1913 to 1920. A multiplication in the number of large steam otter-trawlers sailing from the ports of New England from 32 in 1924 to 64 in 1929, and increase in the catch, by this particular fishery, from 47,000,000 pounds to 119,000,000 during this same interval, illustrate the corresponding increase in the amount of fishing that is yearly done in the American side of the Atlantic, with more and more efficient gear. And wherever, in the sea, fishermen can catch their fares, the story will soon be the same, if it is not so already.

Under these circumstances, the questions immediately urgent of solution with regard to the marine fisheries are: (1) How much fishing can each species now the subject of commercial exploitation stand without depletion at the hands of man? (2) What measures of regulation should be taken to

prevent depletion when danger of the latter seems imminent, or to restore a depleted stock? (3) What is the possibility of extending the fisheries to new grounds? (4) What hope is there of marketing kinds of fish, or other marine products, that are not utilized at present? (5) Can we find a rational basis for predicting in advance the great fluctuations in the abundance of fishes that are known to occur from natural causes, so as to order our fishing efforts more economically?

There has been much discussion as to the degree to which the commercial fisheries have depleted one or another species. Different meanings associated with the term 'depletion' have also caused misunderstandings. If we use it in the sense of reduction, in numbers, of a species to the point when the fishery for it has seriously suffered, this is in fact a danger to be reckoned with in particular cases.

The history of the fisheries includes sundry examples not only of the whales as just mentioned but also of certain fishes, crustaceans, and mollusks that have been fished down to a point where intensive pursuit is no longer profitable on grounds which had yielded abundant fares when first exploited. The halibut of North American waters perhaps affords the most spectacular example of this. Thus, the annual catch brought in by the New England fishermen from the Banks off the Gulf of Maine, off Nova

Scotia, and to the north and east in the Atlantic, fell from about 15,000,000 pounds in 1879, to 3,000,000 pounds in 1926. In the North Pacific, too, it is certain that a decline in the catch of halibut on the older grounds from nearly 300 pounds per unit of gear in 1906 to less than 50 pounds in 1926, and the fact that no more fish are now taken off an 1800-mile stretch of coastline than were formerly caught along 600 miles, has directly resulted from overfishing. The speed with which an overdrain on the stock is reflected in the fishery for the halibut may also be illustrated by the fact that newly developed grounds in the Pacific that yielded 160 pounds per unit of gear in 1923, yielded only 100 pounds three years later, and less still in 1927.

It is generally believed that the great decrease in the catch of albacore off California also reflects too intensive fishing. Similarly, the striped bass has been practically exterminated on parts of the New England coast, though holding its own better along the more southern shores of the United States; the smelt of the northwestern Atlantic fails to hold its own; along certain sectors, European and American, the catch of lobsters per unit of effort has greatly declined since early days, as is also true of the abalone along the coast of California.

Commercial developments on land may also damage the fisheries near shore. The effect, on shellfish

beds, of pollution either by sewage or by industrial wastes is often serious; sometimes directly, sometimes indirectly, as when the oysters or clams are contaminated with the bacteria of human diseases. The damming of tidal estuaries may also have a destructive effect, not only within the basins so created, but by altering the circulation of water in the general vicinity. In fact the probable effect of one project of this sort on the 'sardine' fishery for young herring in the region of the Bay of Fundy (a $2,000,000 industry, based on one of the most important local fisheries of the Atlantic coast of North America), is now causing concern to the fisheries services of Canada and of the United States, for want of the detailed understanding of the biology of the herring, and of the hydrography of the region that is needed for positive prediction.

However, almost all of the clear cases where commercial fishes, or shellfish, have been seriously reduced in numbers have been of species living so close to the land that they are especially vulnerable: the majority of fishes involved are species that enter fresh water at some time in the year, or in certain parts of their geographic ranges. It is an open question whether the hand of man has, up to the present time, appreciably damaged the numerical stock of any of the fishes that support the great offshore fisheries (with the notable exception of the hali-

but, perhaps also of the Pacific albacore), but the fisheries bureaus are now much concerned with the danger that a fishery increasing in intensity may so reduce the average size of the individual fish taken that the total weight of fish caught per unit of effort will seriously decrease. It was the situation with regard to the plaice, with the fears felt for the future of other equally important fisheries in the North Sea, that led the nations bordering on the latter to organize the International Council for the Exploration of the Sea in 1902. And acute apprehension is now felt for the haddock in American waters, because its concentration on grounds where otter-trawlers can easily work makes it especially vulnerable to the rapidly expanding fishery.

It is obvious that if any species be fished down below the limit of safety, the remedy lies in such regulation of the fishery as will allow the stock to recover; whether by closed seasons, by closed areas, or by otherwise limiting the catch. But regulation of this sort must inevitably cause serious disturbance, loss, and hardship to the fishing industry. It is, therefore, of great importance from the economic standpoint to be able to state whether a shrinkage in the catch of one or other of the important species does actually mean that depletion is in progress at the hands of the fisherman.

In the past any sudden decrease in the yield of a

fishery has usually been blamed, forthwith, to overfishing, or to the development of modern methods more effective than those of the past. In fact, whenever any improved method of fishing is introduced, a wail of calamity is at once heard. It is claimed that the young fish are destroyed, the sea bottom disturbed, and so forth and so forth, and investigation is demanded. Such an investigation, for instance, has recently been made of the effect of the otter-trawl fishery in Canadian waters, though this method has been employed for many years off northern Europe and the United States. But when, as often happens, the stock of some fish that had been at a low ebb over a period of years reestablishes itself in the face of a fishery, perhaps even increasing in intensity, it is clear that some factor other than overfishing is at work: the industry then requires protection more than the fish. It has, indeed, been amply proved that the stocks of many sea fishes (perhaps of all) may vary greatly in abundance from year to year, or over periods of years, from strictly natural causes, with which the hand of man has had nothing whatever to do.

Natural fluctuations of this sort have been so freely discussed in the literature of the fisheries during the past quarter-century that it will be enough to mention a few instances here. In general, they mirror the fact that a year of highly successful

reproduction is a decidedly rare event for many species; and that when (by a happy combination of circumstances) such an event does occur, its product may dominate the stock for a long period thereafter, either until they drop out of the picture by the natural death-rate, or until another rich year class is produced. Thus the fish hatched in 1904 dominated the stock of sea herring in Norwegian waters from 1907 until 1919, having supported the fishery for twelve years. Had they not been succeeded by another abundant year class before they died (or were killed), the Norwegian herring fishery would have failed utterly for the time being; and no human endeavor could have staved off the calamity. Off the Newfoundland coast of the Gulf of St. Lawrence the crop of 1904 was likewise responsible for most of the commercial catch of herring as late as 1915. A still more striking example of fluctuations in abundance is afforded by the mackerel in American waters, causing vicissitudes to the fishing industry that have become proverbial: the recovery of the stock of mackerel from its lowest point, in 1910, to its present strength, took place in the face of very intensive fishing.

The fall and rise of the bluefish (*Pomatomus saltatrix*) off southern New England in the late 1700's and early 1800's equally affords a demonstrative illustration of the fact that events of this sort may be

wholly independent of man, for decline, total disappearance, and subsequent recovery of this species took place before any considerable fishery for it had developed. In Norway, the historic record discloses a succession of declines and recoveries in the stock of cod over a long period of years. In Scotland the haddock failed in 1792, but recovered thereafter; the French (true) sardine has also undergone wide fluctuations in abundance, while many other instances of this sort might be mentioned, reaching back as far as the history of the fisheries runs, the economic sequellæ of which have been far-reaching, alternately bringing prosperity and disaster to the fishermen.

The stock of a given species may also be suddenly reduced almost to the vanishing point by some unfavorable shift in the environment; most often by abnormally low temperatures. We have record of such an event as far back as 1789, when seafarers brought back word that the surface of Barents Sea, north of Europe, was covered with large haddock and coalfish in dying condition; probably they had been chilled by some sporadic flooding of the bottom by Arctic water. A more recent and much heralded instance of destruction of this same sort was that of the tilefish (Lopholatilus) off the eastern United States, in the spring of 1882, when vessel after vessel reported these fish dead and dying on the

surface. In fact, the destruction was so nearly complete that it was not until ten years later that a single live tilefish was again seen. But by 1898 they were again as plentiful as ever.

With the stock of any species of fish in the sea likely at any time to diminish, and to stay at a low ebb for years, from natural causes, as well as standing in danger of reduction by man, it is economically of great importance to be able to state in any given instance whether a shrinkage in the catch falls in the one category or in the other, because the procedure proper for the industry to follow may be quite different in the one case than in the other. If depletion be taking place, regulation, as already remarked, is in order; for it is certain that we cannot maintain any of the true marine fishes by artificial propagation if they be overfished. Boast as we may of the billions of young cod, haddock, or others that are dumped into the sea by the government hatcheries, these are less than a drop in the bucket: the product of only a handful of parents in populations to be numbered by the million. But if fish diminish as some one dominant year class dies off, before another year of abundant production has come, it is the fishery that needs to be safeguarded against the disastrous results of a sudden cessation of the supply.

Theoretically, extensive protective regulation might seem called for in this case also. Practically,

however, this has not proved to be the case, because we know of no instance, up to the present, where the stock of a species that has shrunk from natural causes has failed to recover from such a decline in spite of the drain upon it by the fishery. When fish are scarce, there is less fishing done, so that this side of the picture takes care of itself. And the oceanographer stands in the best position to guard the fishery (and the consuming public) against fluctuations of this sort, for he alone has the opportunity to discover a rational basis for predicting such events in advance.

The basic fisheries problem, then, is to make the greatest possible use of the food resources of the sea that is compatible with avoiding the danger of overfishing; and at the same time to help the industry order its undertakings so that it will not suffer from unpreventable fluctuations in the available supply of fish.

Although the problems involved in these two cases are fundamentally distinct, in either case the solution can only come from investigations of the life histories of the fishes involved, and of their reactions to their environment, animate and inanimate, combined with statistical study of the commercial catch. In other words, the technique of oceanic biology must be invoked, whether the aim be protection or prediction. Whenever any fishery increases greatly

in intensity, as happened in the North Sea after the war, and as is now happening with the American haddock, the immediate practical task is in general to estimate the strain of fishing that the species in question may reasonably be expected to withstand: — to determine, in particular, the upper size limit of the individual fish, to which the stock may most profitably, but at the same time safely, be fished down, involving determination of what is termed the replacement — surplus as an index to the safe yield. When any fishery shows a serious decline, the first question is whether this decline reflects overfishing, or whether it results from a natural decrease in the stock in the sea. In either case the species concerned must be studied as populations, not as individuals; methods similar to those developed in the science of vital statistics must therefore be invoked.

The potential usefulness of this line of attack is so widely recognized that the governments of northern Europe, Canada, and the United States have expended large sums for the collection and analysis of catch records and of market measurements. Although the masses of raw data assembled have assumed formidable proportions and although an efficient technique of analysis has been developed, the results, whether in abstract knowledge or in practical returns, have not been commensurate

with the expenditures of money and effort. Thus, to quote the most notorious example, there is no general agreement as to the meaning of the fluctuations that have taken place in the plaice fishery of the North Sea region as a whole, nor in the relative abundance of small and large plaice in the commercial catch, one school explaining the recorded phenomena in one way, another in another, although this fish has been under statistical examination by many hands for many years.

In fact, it is not too much to say that if we regard the time and effort that have been expended in investigations of the sea fisheries as capital, this has as yet returned but a low rate of interest to the fishing industry, or through them, to the consumers ashore.

The basic cause of poverty of result from so great an effort has been the difficulty, when attacking problems of such magnitude and such complexity, of obtaining data adequate to attainment of the ends sought.

The chief deficiencies have been of two sorts: (1) Qualitative defects in the data that have been assembled as to the commercial catches. (2) Inability to carry out the necessary investigations into the basic biology of the commercial species.

Although records of the catch of commercial fishes have been compiled for many years in many countries, in many cases computations based upon

them have been of little value, because the primary data have not classified the origin of the catches in sufficient detail, and because they have not included information as to the methods of capture precise enough to permit analysis in terms of return per unit of fishing effort. As the importance of this last measure seems not to be sufficiently appreciated (outside the fisheries services), it is worth remark, in passing, that a decrease in the total catch of any fish, meaning one thing if accompanying a decrease in the intensity of fishing, might mean something entirely different if it were the accompaniment of an increase in intensity. There are also other obvious reasons why statistics of the amount of fish caught may give an erroneous picture of the abundance of the species in the sea. When purse seiners, for example, take few mackerel, it may simply mean that the fish are too deep in the water to be caught by this particular gear. Or when otter-trawlers report 'few cod,' the latter may simply have congregated on the rougher bottom where the trawlers do not fish; or may otherwise have shifted ground.

The burden of furnishing information sufficient for the compilation of an adequate statistical record weighs heavily upon the industry; it is difficult to persuade individuals and organizations concerned primarily with immediate and pressing business interests to assume this burden, benefits of which ap-

pear to them doubtful or at least extremely remote. Nor has it been possible as yet to arouse a public demand that persons engaged in exploiting natural resources be required as a matter of principle to account in detail for the public property taken. Nevertheless, while the obstacles in the way of obtaining satisfactory fisheries statistics have at times seemed almost insurmountable, improvement is constantly being made. And with progress on this side, the need of similar advances in our knowledge of the life histories of the fishes concerned becomes the more pressing because more and more likely to yield practical benefits.

Here, too, much effort has been expended, and a mass of raw data bearing on various phases has been accumulated and published. But interpretation has lagged, due to our general ignorance of the interrelationships in the very complex chain of events in the sea that govern the comparative success or failure of its inhabitants in the struggle for life. Nothing in the sea falls haphazard: if we cannot predict, it is because we do not know the cause, or how the cause works. The obstacle to the advance of knowledge here lies in part in the technical difficulty of carrying on the needed investigations into the basic biology of the commercial fishes on a scale comprehensive enough to serve as foundation for investigation into particular phases. A more serious

obstacle when seeking support (intellectual or financial) for such work is that in every case the matter is so obscure that it is impossible to predict in advance what particular phase in the fishes' life history will prove to be the vital one, or even that knowledge of any one is more important than of any other. That is to say, the whole life chain must be traced link by link before any sound understanding of it can be reached, which calls for critical and protracted investigations in biology (including physiology), often ramifying into chemistry and physics. Consequently, if the conservation and development of the marine fisheries is to rest on a sound basis, many problems must be attacked in the sea that seem at first sight utterly remote from any practical application. But only recently has it been possible in fisheries investigations to secure the necessary financial support for such work over a period long enough for the study to reach a productive state, and when such problems have been attacked by governmental establishments, the accumulation of raw data has in many cases far outstripped the digestion which is its sole object.

This one-sided development has its reflection in the fact that we do not yet know what precise combination of factors favors or opposes a good year of production for a single species of marine fish.

The question at what age it is wisest to catch and

market the crop of any species, i.e., whether the best yields will result in the long run if the fish are taken near the lower limit of marketable size, or whether they should be allowed to grow larger and to spawn several times, is one of immediate importance in the case of several of the great fisheries, and will become so in the case of others.

Obviously, if a species is to persist, some individuals must grow to breeding age. But as only a fraction of each year's crop can do so in any event (else the universe would be a solid mass of fish) it may be wise for the fishermen to utilize the smaller sizes, most of which could not mature. For instance, we are totally in the dark as to whether the great destruction of immature fish, too small for the market, that is wrought by the otter-trawlers in the two sides of the North Atlantic, and by the pound nets along the Atlantic coast of the United States, so often heralded by calamity-criers, does any real damage to the stock; it may conceivably be a benefit, paradoxical though this may seem. To be more specific, there is no positive evidence that the annual capture of a billion or more of small herring in the Gulf of Maine, to be packed as 'sardines,' year after year, has had any effect whatever on the numerical strength of the stock of adults breeding there. Could a large catch of the latter have been made with equal impunity? We cannot answer. Similarly, it is now

a moot question in what localities it is wiser to protect the small lobsters, but market the large, and *vice versa*; nor can this be settled correctly by argument, any more than can the questions whether large catches of small plaice in the North Sea are really as destructive to the stock as has often been supposed, or whether the size limit to which haddock are now fished down there would prove the wisest in the long run if present methods are continued.

For few species can we intelligently answer the question, Where ought the fish to be caught? — though this may be an important one in the maintenance or development of any given fishery. Practical fishermen have long feared the results of hard fishing on the spawning grounds, especially in the case of the flat fishes, though economic pressure has forced them to do just this, for it is often on the spawning grounds that drift-netting and otter-trawling are the most productive. On the other hand, we already know that there are certain grounds where no amount of fishing for certain species (even to the verge of temporary extermination) will have any permanent effect upon the general stock. This applies in cases where there is a regular emigration away from the spawning areas to grounds far distant, with no return migration. Thus the lobsters that stray to the Bay of Fundy cannot reproduce in the low temperatures prevailing there,

though they find these cool conditions favorable to mature growth. It would be pure economic waste not to catch them; but is wisest to allow them to grow to large size before doing so. The case is apparently similar for the stock of rosefish (Sebastes) off the west coast of Greenland, which are largely recruited from fry produced in high temperatures in the Atlantic to the south. In such cases the only sound limit to fishing is the economic one. But the understanding of instances of this sort involves a knowledge of the lines of dispersal and migrations in general, which in turn may demand long-continuing study (by all available methods) of ocean currents as carriers of eggs and larvæ; and of the length of time during which these latter drift at the mercy of the current; information which, again, can only be gained at sea.

Another factor in determining where (from the standpoint of conversation) it is wisest to fish is the extent to which grounds where cod, haddock, and so forth, are little fished at present serve as reservoirs of supply for banks fished more intensively because more accessible; what protection, if any, should they receive on this score? That banks do serve as reservoirs for one another in this respect is certain, because when small grounds close to land are so fished out that it no longer pays to visit them (as happens often, and sometimes very soon) they

presently recover if the fishermen abandon them for a term of years. In fact, a power of rapid recuperation seems almost an invariable law in the sea; any species, indeed, that did not possess this power would soon vanish from the scene, fishing or no fishing, by so many dangers and so constant are they all beset. What rôle in this recuperation is played by immigration from surrounding grounds, what by local reproduction? In the case of the Pacific halibut this is a live question today, and the answer to it will govern the regulations to be adopted. Its solution can only be reached through a study of migration, and of the factors determining the success of breeding, so that the International Fisheries Commission is governing its procedure accordingly.

At first sight it might seem that the question 'how' best to harvest the crop would be purely economic, not biologic. Actually, however, this is not the case, for many reasons. Thus different kinds of gear take fish of different sizes, while the type of gear used may also determine the fishing grounds frequented, and the depth zone available for fishing. The otter-trawl, for instance, can be used only on comparatively smooth bottom, the purse seine only close to the surface, and in smooth weather; the pound net or weir only close to the shoreline, and only during the warm months if ice forms during the winter; hook and line only where fish are feeding, and so

forth. Whether the grounds, depths, or seasons, so determined by the method adopted, are wise from the standpoint of conservation, or the reverse, can be settled only by knowledge of the life history of the particular fish.

'How to fish' has another biological aspect that cannot be neglected: namely the effect that the fishery may have on enemy-species that are caught incidentally, or on species upon which the commercial fishes prey. Any method that will take and destroy large numbers of destructive species may actually benefit the primary object of the fishery, in spite of the draft that fishing makes on the latter. In North American waters this applies especially to the destruction of dogfish, of skates, and of the goose — or monkfish (Lophius). But off other coasts, where the last two are used for food, the relationship is different. To destroy annually several hundred million menhaden (Brevoortia), as is done to supply the demand for fish oil and for fertilizer, may seriously lessen the food supply for the bluefish (Pomatomus), and so react against the latter. But the lives of so many menhaden are saved whenever a bluefish is caught that its death may be economic gain. The interrelationship of different species, as food or enemies, is thus a vital factor in the situation; to disentangle this skein falls directly within the province of the oceanic biologist.

Ever since man first cast line into the sea, Can we broaden our fishing grounds? has been a live question. With the passage of the years one new fishing bank has been developed after another, and no one can dispute that the discovery of new grounds and of new bodies of fish from which no toll has previously been taken, is so much pure gain. Practical fishermen and fisheries bureaus are therefore interested in testing the possibilities of unfinished parts of the sea by actual fishing experiments, such, for instance, as have been carried on during recent years in South African waters. Although it is certain that the major fishing grounds off the North Atlantic coasts of Europe and of North America are already being exploited extensively — so, too, off the North Pacific coast of North America — some extension may be expected even there; witness the development of a productive fishery in water deeper than the local trawlers had previously frequented for hake (Merluccius) as recently as about 1903. And much greater possibilities of expansion still remain in the Gulf of Mexico, in the South Atlantic, in the eastern and western Pacific, and in the Indian Ocean, as well as in Arctic and Antarctic Seas. Less direct methods have also proved fertile from this standpoint. For example, highly productive cod grounds have been developed off Norway by deducing the existence of spawning schools from the dis-

tribution of their eggs floating at the surface of the water.

The question of extension of grounds is, however, not a simple one of exploration, because expansion might in certain cases prove detrimental to some of the most important species. For example, it is questionable whether the stocks of sea bass (Centropistes) of scup (Stenotomus) and of various other fishes that vanish from the eastern coast of the United States in winter can stand the added strain of the year-round fishery that is developing now that their wintering ground has been found.

The possibility of discovering new fishes, or of mapping the centers of abundance for species whose existence has long been known but which have not been made the object of any regular fishery, because their abundance is not suspected, is closely associated with the development of new grounds. One might hardly have expected that the existence of a large and valuable food fish, in great abundance, and close to the fishing ports of the eastern United States, would have remained unknown until 1879. Such, however, was the history of the tilefish. The first specimen of this species was brought in by a fisherman, but it needed the explorations of the United States Bureau of Fisheries to make its geographic distribution and abundance known and to introduce it to the market. Thanks to these efforts,

the tilefish has of late yielded much good food. And while history can hardly be expected to repeat itself in so spectacular a way in the North Atlantic, unlimited possibilities for this sort of expansion are still open in the other oceans. In fact, the sea is certainly capable of yielding vastly more food to man than at present. There are also attractive possibilities of expanding the yield of fish products other than food, especially fertilizer, stock food, oil, glue, and so forth, and fish skins as a source for leather. In fact the catch of one species alone (the menhaden) used exclusively for fertilizer, scrap, and oil along the Atlantic coast of the United States, is about 700,000,000 pounds yearly.

In the case of the shell fisheries (for clams, oysters, mussels, abalones, pearl-oysters, lobsters, crayfishes, crabs, shrimps, prawns, and so forth) the great problem is to guard against depletion by overfishing, or to replenish the stock by cultural methods. This danger is much more imminent for the mollusks and for certain of the crustacea (lobsters, crabs) than it is for most of the marine fishes, because these (including all the mollusks now used for food) live close to shore in shoal water; also, in the case of mollusks, because they are so stationary that once a center of abundance is found, it is soon fished with great intensity. The result is that the maintenance of the stocks of oysters, clams, abalones, and so forth,

around our coasts is already an urgent matter, and it has been found necessary severely to regulate the pearl fishery wherever this is carried on in the Indo-Pacific. To emphasize the economic importance of the shellfish (mollusks, lobsters, crabs, and shrimps) we may point out that they form about one fifth [1] of the total sea foods harvested from the Atlantic coast of the United States, while oyster shells also yield about 6000 tons of lime there, as a by-product, yearly.

The stationary nature, however, of these mollusks, and the possibility of cultivating them, as is now successfully done with clams and oysters, makes it easier to safeguard them than the fishes. But detailed knowledge of their lives and ecological relationships is an absolute essential, not only for cultivation, but equally for regulating the catch from grounds, or of species not susceptible to cultural methods. And this knowledge can come only from detailed studies falling in the field of marine physiology.

In short, every problem of the marine fisheries, except such as center directly around the education of the human palate to appreciate new foods and of human industries to employ raw products from new sources, or around improved methods of distribution, handling, and marketing, is a problem in oce-

[1] Oysters and clams figured without their shells.

anic biology by whatever technique it be attacked, just as every problem in plant or animal husbandry on land is one in terrestrial biology: consequently, a problem falling directly within the direct scope of oceanography. Every such problem demands for its solution precisely the procedure that would be employed had it no economic bearing whatsoever; results gained in any other way can never be better than haphazard; i.e., of the sort proper to a past age.

This means that whatever marine animal be in question, whatever be the immediate question regarding it, and whatever method, statistical, observational, or experimental be employed for the solution of the latter, an understanding of the whole life cycle of the species must finally be arrived at for a complete answer: fisheries biologists have long appreciated this truth. And a growing demand for information on such points as spawning grounds, rate of growth, feeding habits, and migration, is evidence that the fishery industry is also coming to realize it.

It is no reflection on science that only certain of the links in the life chain are yet known for any fish in the sea, because every case is one of great complexity, involving, *inter alia*, the physiological state of the parent as determining the viability of the eggs and sperm; the temperature and salinity of the water as governing the hatch; the character of the eggs,

whether buoyant or not; the duration of incubation, and the drift of the water as governing their dispersal; as well as the supply of food — unicellular plants or minute animals — available when the little fishes hatch: this last is probably the most vulnerable stage. The toll taken of the larvæ by enemies is also important. Probably these headings include the factors that chiefly govern the relative success of reproduction from year to year; hence to understand the natural fluctuations of the stock, knowledge of these factors is as essential as is knowledge of the inroads made by man for understanding the effect that the fishery has upon the crop of adults. But it is about precisely these matters that we still remain in the deepest darkness. Such investigations in their ramification also involve the life histories of various species of plants and of animals that may either serve the fish in question as food in one stage or another of its development, that may serve as the food of its food, or that may prey upon it. Whatever reacts favorably or unfavorably on the one, will react likewise on all the rest.

It is no wonder, then, that fisheries biologists have harped on the practical importance to fishermen, and so, in turn, to the purse of the consumer, of the welfare of the minute creatures in the sea on which young fishes feed, finally harking back (*via* their own food) to such elemental matters as the salts in the

sea, and the amount of sunlight falling on the surface of the water.

The direction and duration of the involuntary or passive migrations of the larvæ, their food, their rate of growth, and the age at which they either take to the bottom or begin to direct their own journeys, is one factor; wanderings of the older fish, the other, that governs the interchange of fish between different banks, and the degree to which certain grounds serve as nurseries for others. This, with the importance of temperature as a vital factor, makes the study of the ocean currents one of the most important items in fisheries research today. Knowledge of such matters as the food and spawning habits of the adults, of their rate of growth, of the dominance of particular year classes, of the enemies, of the general distribution, and of the optimum temperature and salinity for the older fish are equally essential for intelligent management of the fishery.

There is nothing fanciful or extreme in the foregoing: to cover the whole field must be the ultimate aim if measures of conversation are not only to be effective, but at the same time are to impose the minimum of hardship upon the fisherman. This, in principle, is now accepted by all who concern themselves with the preservation of the deep-sea fisheries, as illustrated by the program of the Inter-

national Fisheries Commission, charged by treaty between the United States and Canada with the proper regulation of the halibut fishery off the northwest coast of North America. Rapid depletion makes regulation necessary in this case, as already remarked (page 195). In fact, as the United States Commissioner of Fisheries has pointed out, the fishery is in a very serious condition from overfishing. But to arrive at a basis for action, the Commission has found it necessary to search for the eggs and larvæ, to map the drift of the same, to examine the dynamic oceanography of the region as governing this drift, to trace the wanderings of the adult halibut, to chart the spawning grounds, and to trace the interrelationships between the stocks of halibut on different grounds.

When seeking a basis from which to predict the productivity of a fishery, for a given season or period of years, an essentially similar method of procedure is requisite. The United States Bureau of Fisheries has, for example, undertaken an intensive study of much these same phases in the life history of the American mackerel, hoping to be able to warn the industry, in advance, of the violent and uncontrollable fluctuations in the number of mackerel existing in the sea that come from natural causes. And though this study has been in progress for only four years, predictions of the mackerel fishery for 1928

and 1929, based on the state of the stock in 1927 and 1928, were close to correct. Predictions of the abundance or reverse of herring and of sardines in European waters, based on similar studies, have also been successful enough to justify the hope that they will be of great and increasing value as a better knowledge of the governing causes is gained.

It is idle to suppose that oceanwide expeditions, undertaken at long intervals, will be of much value in advancing investigations of this sort. What is needed is intensive study either of regions, of individual species, or of particular fisheries, as the case may be. These must be so long continued (because covering so wide a field and concerned with the natural economy of generation after generation), and so intensive (because of the nature of the problems involved), that individual investigators can make but slow progress. In no field, in fact, are joint efforts and the services of coöperative agencies more needed in oceanography, than in fisheries biology; and in none is it more necessary to give attention to problems that may at first seem remote from any direct economic bearing.

## 2. Navigational Problems

In a general way, the sea now serves man's purposes adequately as a high road for commerce. But now and then, even in this era of full-powered

steamers and elaborate safety devices, we have brought home to us in a tragic way that the sea still has its dangers: we may be shocked to hear of a collision with ice, as chanced to the 'Titanic' in 1912; of the foundering of a steamer, its plates stove in by the force of the sea; or of the stranding of some ship put out of her reckoning by an unexpected current. The high rates of marine insurance, as compared with insurance on goods in transit on land, mirror the risk to property run on every passage.

Probably the greatest gain that oceanography could offer in cheapening, expediting, and safeguarding commerce on the seas, and the only considerable gain to be hoped from it in this respect at present, would come from adding detail to our knowledge of ocean drifts and of tidal currents, and of the depths of water off coasts not yet accurately chartered.

The importance of ocean currents in ordinary day-to-day navigation is so obvious as to need no emphasis here. Ignorance of the direction and velocity of the current is responsible for some of the discrepancies between the true position of the ship as determined by astronomical sights and that calculated for her by dead reckoning, though log errors, bad steering, leeway, and so forth, all enter in. A recent example of the tragic effects an unrecognized drift may have is afforded by the difficulty

that ships coming to the assistance of the ill-fated 'Vestris' had in finding her; the fact that she was more than thirty miles from the calculated position, in a run of only two days, being perhaps best explained in this way. And many wrecks have been caused by ignorance of the direction and strength of the current near shore at the time.

It is self-evident that to follow a favoring current hastens, to stem a contrary current retards, passages. This is made particularly true off the east coast of the United States by the proximity of the so-called 'Gulf Stream,' the drift of which must always be taken into account. Every hour wasted steaming against the current entails so much extra cost; wherever it is possible to go with the drift, fuel is saved. And either small savings, or small losses, when cumulative, reach staggering proportions in the course of years. This factor is of far greater moment for the slow freighters, in which most of the world's maritime commerce is carried, than for the fast passenger liners which can often disregard the current. In parts of the South Atlantic, Indian, and Pacific Oceans we still lack sufficiently detailed knowledge of velocities and precise directions of the currents, of the effects on these of varying winds, and of seasonal variations to allow intelligent planning of routes for slow ships, even though the general characteristics of the oceanic circulation are understood.

The aggregate economic loss from such ignorance, if measured in dollars and cents, would be very large. Even when the current arrows are true enough as an indication of the mean direction, the actual drift at any given date may differ widely from that shown, and this is what the navigator wants to know.

This need of bettering our present knowledge of the major currents is fully appreciated by the hydrographic services of the seafaring nations. For this reason the British Admiralty, the United States Hydrographic Office, and the German Marine Observatory, among others, are continually accumulating a vast amount of data from vessels' log books, as well as from all other available sources, in the hope of improving their yearly and monthly current charts. Such information is, of course, most important for the regions where the direction of the dominant drift reverses from season to season, as in parts of the Indian Ocean; or which fall within the sweep of a great current at one season, but not at another; or over which the daily velocity varies greatly from season to season with varying winds.

In certain regions, as along the west coast of Africa, and in the Red Sea, rapid advances in knowledge of the currents have been gained within the last few years. But to illustrate the urgent need of still further improvements even in more traveled

seas, we need only instance the present vagueness of our understanding of the secular variations in the geographic location of the inner edge of the Gulf Stream drift off the east coast of North America, and of the eddying movements plus counter drifts that confuse the orderly procession of that body of tropic water toward the northeast. That the Gulf Stream has shifted its position is a frequent report; one, too, that includes more than a grain of truth. Knowledge of the southerly drift along the west coast of North America is still vague. More detailed information is made especially urgent there for the sake of safety at sea by the scarcity of good harbors of refuge along the coasts of Oregon and California. And 'sketchy' fairly describes our present picture of the currents among the Polynesian, Philippine, and Malayan Archipelagoes, to mention only a few striking instances.

Ocean currents affect navigation indirectly as well as directly, and in a disastrous way, by bringing icebergs and field ice down from the Arctic, a frequent menace to the shipping lanes between America and Europe. This danger the maritime nations now meet in part by maintaining the International Ice Patrol, during the danger season, in the region of the Grand Banks of Newfoundland, where the steamer routes between the United States and northern Europe touch the principal lane followed

by the bergs in their drift southward from Davis Strait. Betterment of this patrol demands more detailed examination of the variations in the two great currents (Labrador and Gulf Stream) that meet here, the first bringing the bergs, the latter melting them, for it has been appreciated, from the beginning, that the task of following the drifts of individual bergs would be greatly facilitated by knowledge of the circulation of water in the region as existing at the time. The dynamic and other hydrologic studies that the patrol cutters carry out, with this end in view, are therefore of direct economic value. To gain a sounder understanding of the factors that control the journeyings of the ice, the service has recently expanded its activities to include a dynamic survey of the whole region between Labrador and Greenland, as described in another section (page 103). And should the patrol be extended to include the more northern routes, it will become increasingly important to make periodic surveys of these northern waters in the hope of explaining (perhaps predicting) the wide variations in the amount of ice that comes southward from year to year, and the varying tracks that the bergs follow.

As demands grow for an extension of maritime trade routes more and more to the north, the need of detailed information as to the state of the Arctic ice from season to season correspondingly increases.

Thus it is a live question how many months in the year open water can be depended upon in Hudson Strait and in the northern and northeastern parts of Hudson Bay, for the answer will determine the practicability of developing the harbors on the Bay as export centers for wheat, and so forth, from the Canadian Northwest, in competition with the harbors in the Gulf of St. Lawrence and to the southward. In this case the drift of ice from the north will govern, not the ice frozen locally in these comparatively low latitudes; a drift, in turn determined by the dominant movement of the water in its course out of the Bay and through Hudson Strait. The Canadian Government is fully alive to the importance of this matter, and has already sent several expeditions to the Strait.

The rapid development of air navigation, leading to attempts to develop safe flying routes over the top of the world (to shorten the distance between America and northern Europe), gives added significance to the state of the ice in the Arctic, especially to the northward of Spitzbergen, from season to season, and from year to year.

For these navigational reasons, as well as in the interests of the fisheries (page 219) and for the general advancement of science, we need not only a better knowledge of the circulatory events in the sea, but better understanding of the basic forces that keep

the ocean currents in motion, as well as of the relative effects of the conflicting factors that influence their set and drift. This cannot be gained by continued compilation of log-reports, no matter how extensive, because the underlying waters are involved, as well as the surface. Quite other procedures are called for, as described above (page 98). Work of this sort, however, can seldom be attempted on a large scale by any governmental establishment, because the difficulty of demonstrating an immediate economic result makes legislative support difficult to win. And while the development of methods of attack, and so forth, often draws inspiration from one or another isolated center or individual, successful application to the oceans demands coöperation between many institutions, because the field is ocean-wide. Observations must also be carried on for many years to trace the long-time fluctuations that are already known to occur.

In many parts of the world the tidal currents run with velocities much greater than those of the ocean drifts on the high seas, and they are usually strongest next to the land, just where ships meet their greatest danger.[1] In fact they may play their greatest economic rôle within busy harbors.

[1] Contrary to the belief among landsmen, the well-found ship is safest when far out at sea: when skirting the land, she is in constant risk.

It is easier to study tidal currents than ocean drifts because most of the work can be done near land, in shallow, and often within enclosed waters. Under such conditions the direction and speed can be measured directly from hour to hour as the tide ebbs and flows by current meters, by chip-log, or by float. And an enormous amount of this work has been done by the tidal services of the different countries, including continuous observations over periods of many weeks or months at strategic locations (lightships, for instance). But while the stage of the tide can now be predicted in advance for any time of the day with great accuracy for most of the important harbors of the world, knowledge is far less advanced concerning the velocity and set of the tidal currents. Current surveys with this end in view are now being carried on along the coasts and in the more important harbors of the chief maritime nations by their respective surveys, but progress, necessarily, is slow with the appropriations available. And for administrative reasons the coastal and tidal surveys of the different governments are seldom able (never able in the case of the United States) to extend this work beyond their own coasts or those of their dependencies. Even in frequented waterways, other than harbors, present information is, in most cases, insufficient — witness the necessity the engineers for the projected tidal-power development in

Passamaquoddy Bay have been under of making their own survey of the strengths and directions of the tidal currents there. Knowledge of the latter is even more elementary around the shorelines and in the bays and estuaries of all the countries that are more backward in this respect, for what is known of such regions has necessarily been gathered more or less haphazard, as opportunities offered for some man-of-war or other ship to take current measurements while on foreign station. The paucity of detail as to the direction and velocity of the tidal currents given in the sailing pilots for South Atlantic coasts, for the island groups of the Central Pacific, and for the Eastern Archipelago will make this clear. And nowhere, in the open ocean, is it yet possible to predict the pure tidal current, because the latter is so often complicated by the wind, and by whatever non-tidal drift may dominate the region in question.

Here a wide field lies open for oceanographic research, where knowledge gained will sooner or later be of practical advantage to the navigator.

Knowledge of the topography of the sea bottom — i.e., of the depth of the water — along the coast is, to the navigator, as important as is the detailed charting of the coastline itself. Not only does his ability to enter harbors in safety depend on this knowledge, but by sounding he can feel his way, and often can

locate his position, when fog or storm hides every visible mark, terrestrial or celestial.

Until very recently it has chiefly been in comparatively shoal water, say less than one hundred fathoms, that soundings have been helpful to the navigator, and the importance of mapping the depth near land in the greatest possible detail has so long been fully appreciated, and so much effort has been devoted to this, that existing charts leave little to be desired for navigational purposes, for the more frequented coasts.

An example of the accuracy of some of the older shoal water work is afforded by the fact that charts of the Maldive Group in the Indian Ocean, based on soundings taken nearly a century ago, are so accurate that no appreciable errors were found in 1901–02 except such as would naturally result from subsequent growth or death of coral heads. Even off the coasts as well known as those of the northeastern United States, however, pinnacle rocks have recently been discovered, and surveys must be repeated at frequent intervals off sandy coasts and inlets where bars shift and channels change. In fact, few laymen appreciate the extent of the coasts where knowledge of the depth is still more or less imperfect, or in need of frequent revision. For an example we need seek no further than the east coast of Labrador, where soundings are not only so few, but so many of them

inaccurate, that a stranger must proceed wit greatest caution, while considerable stretches c coastline itself are still to be filled in on the ‹ In Alaskan waters employment of the 'wire method has recently added much importaı formation, especially as to the location of pir rocks, such as are apt to be overlooked in other of surveys.

Now that sonic methods of sounding have re the stage of practicability, the application of urement of depths to navigation enters a new ] In the first place it is now possible to survey a area much more rapidly than by the old me' In the second, detailed information of the edge slopes of the continents becomes increasingl portant, for as more and more of the larger shı stall sonic gear with which they can sound a depth while running at full speed, they find it and more helpful to pick up the slope as an in‹ their distance from land, in thick weather. Th International Ice Patrol, during the season of found the sonic fathometer of great assistar navigating in the fog around the slopes of the ( Banks of Newfoundland; had these slopes been chartered the cutters could have placed much dependence on the positions indicated by thei soundings.

## 3. Currents as Affecting Harbor Construction and the Protection of Shore Property

We can only reiterate what was pointed out at the Conference on Oceanography at the United States Navy Department in 1924, by General Edgar Jadwin, that the direction of the current must always be taken into account in planning harbor entrances on sandy coasts in order that the entrance jetties may be designed and constructed either to catch and hold the drifting sand, or to divert the latter past the entrance so as to prevent the filling of the channel with sand. The currents of importance in this case are those close along the tide-line; and at the times when these are strong enough to drift the sand along the shore, they may either be parallel to or opposite to the general dominant drift offshore, depending on the direction from which the storm waves travel, and the angle at which these strike the coastline. At the tip of Cape Cod, for example, the only storms that drive heavy enough seas against the beach to move much sand are from the eastern quadrant. Consequently, the beach drifting is toward the west and southwest, whereas the dominant movement of the water only a short distance offshore is in the opposite direction.

In any given case, therefore, a more detailed knowledge of beach drifting is requisite than has yet been gained for any considerable sector of the North

American coastline. An attempt made to reopen New Inlet, Dare County, North Carolina, affords an excellent example of what is apt to happen when harbor work is undertaken in ignorance of the beach currents. This inlet, which had closed shortly previous, was dredged open by the State of North Carolina at a large expense. But because of ignorance of the movements of the water along the beach, the channel was not protected against the drift of sand. The result was that before three months had passed the cut had entirely closed again, all the money that had been spent on the work was wasted, and the benefits that reopening of this inlet would have brought to the local fishery were lost. A small sum spent on studying the beach drift there, during storms, would have safeguarded work worth many thousands to the State.

All this applies equally to construction undertaken to protect shore property, much of which has defeated its own purpose, by setting in motion unexpected currents that have cut into the very stretches of beach they were planned to protect.

### 4. Soundings in Connection with the Laying of Submarine Cables

An accurate knowledge of the contour of the bottom of the ocean is essential for the laying of submarine cables. The more detailed the knowledge of

the general region, the better can routes be planned to avoid the ridges and depressions of the sea floor, and the more precise the knowledge of a particular route, the less the surplus length, or slack that must be allowed to guard against unknown irregularities of the bottom. Such matters are being investigated along most of the existing cable routes, by commercial cable ships that carry on the work of repair and renewal, which are equipped with the best sounding gear yet developed.

As the commercial demand increases, new cables must be laid along new routes, across parts of the sea which, to date, have been but sketchily surveyed. It has been stated, for instance, that an adequate survey of the Japan Deep and of neighboring regions would be especially valuable from this standpoint, because lying in the route which will probably be chosen when additional cables are laid across the North Pacific, while projects to connect up the American with the British trans-Pacific cables will entail surveys between the Hawaiian and Fanning Islands. A survey is also needed direct from the Panama Canal to Honolulu; also additional information all along the Pacific coasts of South Central America, and South America, including those of outlying islands (the Galapagos, for instance), that might sometime be chosen for relay stations. As soon as commercial development in the

southern hemisphere demands the extension of the present cable systems across the South Atlantic, South Pacific, and Indian Oceans, information far more detailed and accurate than is now available will certainly be required as to the depths and shapes of the bottom. The recent expedition of the 'Meteor' has given a preliminary picture of the bottom of the South Atlantic, but (from the cable standpoint) no more, and we believe we are correct in stating that until the 'Carnegie' undertook her last cruise, only one line of sonic soundings had been run across the South Pacific, this being the only method yet discovered by which detailed surveys of large areas of deep ocean can be made economically. The 'Carnegie,' before her destruction, and the 'Dana,' have added several profiles in the North and South Pacific, but vast areas in that ocean still remain virgin so far as detailed knowledge of their submarine topography is concerned, as remarked in an earlier chapter (page 22), which applies equally to the Indian Ocean.

According to a statement by Colonel C. A. Seone, to the Oceanographic Conference at the United States Navy Department, 1924, it was usual until very recently — i.e., so long as soundings in deep water could be made only with wire — to allow ten per cent excess length, or slack, to provide against unforeseen irregularities of the sea bottom. And it is

not likely that any cable had been laid over a long distance with less than eight per cent of slack, until methods of sounding by echo were developed. Taking advantage of this improvement through surveys made by the United States Navy, the United States Army was able to relay its Alaskan cable with considerably less slack than ever had been done before, at a corresponding saving in cost, thanks to the more intimate knowledge of the topography of the bottom so gained. We are informed, however, by an official of one of the largest cable companies, that a method of measuring the depth in deep water more exactly than can be done with the sonic devices now in common use would be of great assistance in locating the ends of cables when broken, as happened to eleven off Newfoundland during the earthquake which shook the seaboard of the northeastern United States and Canada in November, 1929.

## 5. Oceanography and Seasonal Weather Forecasts

The question whether or not a rational basis for forecasting any features of the weather, for any part of the world, can be found in the variations that take place in the temperature of the sea, has been much discussed of late, both by meteorologists and by oceanographers.

In introducing this matter we must point out that its present economic status falls in a category quite different from that of the phases of oceanography already discussed in this chapter. The economic bearing of the exploration of tidal currents, for example, of the charting of coastlines and harbor approaches, or of the sounding-out of shoals is not only direct but immediate; that of many specific problems in fisheries biology is equally direct, if less immediate; and the practical importance of the more general phases of oceanic biology is unquestioned, if more remote. But there is, as yet, no general agreement whether, or to what degree, forecasts of the weather, based on the temperature or on any other feature of the water, can ever be made reliable enough to prove of general service to man, unless it be in specially favorable regions.

The first economic problem, then, to be solved in the oceanographic investigation of the interaction between sea and air is whether this does indeed offer reasonable prospect of yielding direct practical benefits as some meteorologists now confidently maintain but which others as confidently dispute. This ground is at present so controversial that the oceanographer must tread warily.

Furthermore, a clear distinction must be drawn between the type of weather prediction that could be furthered by studies of the atmosphere itself over

the oceans (this is not a part of oceanography), and the type for which some meteorologists believe a rational basis can be found in the variations of the thermal state of the water. The first corresponds mostly to the sort of daily weather charting and forecasting now carried out on shore. If enough stations could be arranged for, properly distributed over the oceans, it would be possible to forecast the tracks of storms, directions of winds, and state of the weather a day or two in advance over the sea just as is now done on land. Meteorologists—the shipping interests, too—have long realized the desirability of such forecasts. The reason that their development has lagged in the past has been the difficulty and prohibitive expense of organizing a sufficient number of recording stations, the necessity for taking all observations from ships which makes it impracticable to establish fixed stations, and the weakening of the chain that would result from a failure to obtain regular reports from the less frequented seas. An attempt to meet these difficulties is now being made by the several weather services, by the designation of certain ships as reporting stations according to a uniform plan. The data so collected may be expected to serve as the nucleus for statistical studies, embracing also the vast amount of data that is concurrently collected by the great maritime nations.

There is no reason to suppose that any study of the

surface temperature of the sea, of the evaporation, or of the variations in the ocean currents, no matter how detailed, could ever assist the general daily forecast, whether for sea or for land, because whatever changes take place within the sea (either with the alternations of the seasons or following extra-terrestrial causes) are events inordinately slow as contrasted with the sudden fluctuations in the atmosphere. The goal that some students believe attainable here is quite a different one, namely, reliable prediction of the seasonal weather character over the adjacent lands to leeward: even over lands far distant.

Ordinary weather forecasting, such as is now carried on by most of the civilized governments, has become so much a matter of course, is usually so well verified and is so universally used as a guide, that there is a constant demand for longer range predictions of just the sort that the proponents of forecasts based on sea temperatures hope to see realized; namely, to tell us weeks or months in advance whether high or low temperatures, much or little rainfall will prevail. Even in regions where the weather fluctuates widely from day to day it would, in many cases, be of great economic value to know in advance the direction of abnormality to be anticipated in these respects, even if its amount could not be foreseen. Thus a departure of a degree or two, plus or minus, from the normal temperature in

winter may govern whether most of the precipitation of a northern region comes as rain or as snow, correspondingly affecting the ease of transportation, and so forth. Advance information of this sort would be so helpful a guide to many industries (we need only instance the clothing trades, power and transportation companies, and certain branches of agriculture), that attempts in that direction are constantly being made. And proof that industry as a whole would actually welcome assistance of this kind is found in the fact that many concerns are willing to pay high for such forecasts, even while realizing that their dependability is yet to be proved.

Forecasts of this type have been given out from one source or another in various parts of the world. Some of them have had no physical basis, while the sponsors of those few that have would be the first to declare that the data for their calculations have been far from adequate. Even such of the long range forecasts as are based on tangible factors have in most cases been purely empiric: deduced, for example, from astronomical cycles (planetary or solar), from correlations, or on the assumption that a periodicity recorded in the past will recur in the future. In most cases, publication of these forecasts has been abandoned before long, discredited by too frequent failure, on the part of the weather to substantiate the prediction. And it would certainly be premature to

claim that any one has yet worked out a dependable sequence from antecedent events, whether in sky, in sea, or on land, from which the weather to come can be forecast far enough in advance for any considerable part of the earth's surface, or reliably enough year after year to serve as a trustworthy guide for man's activities.

This, however, does not necessarily mean that such a sequence, or sequences, cannot be found: on the contrary, there have been some promising developments of late. Thus government forecasts of the summer monsoon rainfall of India, based on oscillations in atmospheric pressure at stations bordering the Indian Ocean, have been reasonably successful in the long run, and well verified in occasional years, though poorly in others.

It has also been suggested, repeatedly, that at least a partial basis for such a sequence could be found in the sporadic variations that are known to take place in the surface temperature in various parts of these a, combined with any corresponding expansions or contractions of the ocean currents, and with the rate of evaporation from the surface. This is now being tested by the various comparisons between the physical state of the sea water and the local weather that are being carried on at present, especially for the North Atlantic; in Canada; in California; and in Java. For example, marine temperatures are now

being used in an attempt to determine whether the weather in Europe or in the South Atlantic part of the United States shows dependence on conditions in the Gulf Stream. Predictions of the weather of Southern California developed at the Scripps Institution from the temperature of the adjacent sea during the preceding months have been verified to an encouraging degree for the past twelve years, with winter rainfall on land greater than normal when the neighboring sea has been cooler than usual during the preceding August–October, and *vice versa*, while attempts to forecast the amounts of rainfall have been about seventy-five per cent verified. Long-range forecasts based on similar factors are also being issued commercially from at least one private source in the United States, though so far as we are aware no independent analysis of the degree of verification has yet been attempted in this case.

It is obvious that studies of this class, if looking toward weather prediction based on oceanic temperatures, presuppose the occurrence of longer or shorter term fluctuations of temperature in the sea, of a sort that cannot be described as regularly 'seasonal.' And as pointed out on page 60, this supposition is amply justified, such variations having been observed so frequently in every part of the sea where the temperature has been studied in detail that they must be accepted as characteristic. But be-

fore the claim that these events can be used as a basis for weather prediction can be upheld it is necessary to establish, not only that a regular correlation exists between the two classes of phenomena for the parts of the earth in question, but that the changes in the sea regularly antedate the changes in the atmosphere, and not the reverse; also whether the former are so great that their effects are not entirely masked by the complex atmospheric phenomena that immediately control the weather.

This quantitative aspect of the problem is especially pressing because meteorologists and oceanographers have mostly to do here with minor fluctuations in the thermal state of the sea, seldom with major alterations of a sort that would strikingly be reflected in the weather of some part of the world, such as the heavy rains over parts of the Peruvian desert early in 1925, or the droughty and other consequences of unusual outbursts of polar ice. Though it is certain that minor fluctuations do occur commonly, little is known about them except in the marginal seas in high latitudes (just where they may be expected to reach their widest range). And while a progressive movement of such temperature abnormalities as develop may be expected to take place along the tracks of the major ocean currents, precise information on this point is much needed.

In the northern hemisphere, for example, easterly

movements of this sort have most frequently been traced in latitudes north of the fortieth parallel. But this may partly be because the temperature abnormalities so far actually recorded (not surmised) have been much greater in high latitudes than in low, allowing their progression to be followed more certainly. To illustrate the difficulty of tracing, across the oceans, the small thermal variations that have been recorded in the tropics, from the usual records supplied by passing ships, we may instance the Caribbean Sea where data tabulated by the United States Weather Bureau for the nine years 1920–29 showed a maximum monthly departure of 1.2° F. from the mean; with only 39 months of the 100 showing deviations greater than .5° F.

The crux of the matter is, however, to establish beyond reasonable doubt whether, or in what parts of the ocean, temperature abnormalities or other changes in the water do actually antedate alterations in the weather of the overlying air with regularity. Nor can any general rule be assumed to apply, *ipso facto*, in this respect, whether regionally or seasonally, the whole question being an extremely complex one. The sequence is not yet clear, even for regions where sea and air temperatures have been under observation for many years. In the Gulf of Maine, to note a single example, it is sufficiently demonstrated that the temperature of the air and

direction of the wind largely control the temperature of the water in winter. However, the subsequent effects on New England weather of these weather-produced water temperatures are unknown. Off Southern California, again, the wind affects the temperature of the surface both by producing upwelling from below, and by sweeping cold water down from the North. How these temperatures react on the temperature of the air, and so on the weather, is now the subject of active investigation at the Scripps Institution. It has often been stated that for Scandinavia various atmospheric and terrestrial phenomena follow the cycle of sea temperature. But recent students have found the sequence to be the reverse, for, while a close correlation has been shown to exist between air and water temperatures along the coast of Norway, it now seems that the variations in air temperature precede those in the water more frequently than the reverse. Nevertheless, this does not necessarily indicate that the atmospheric changes are the primary ones in such cases, for the more mobile air may bring departures in temperature to a given coast more rapidly than the warmer or colder water can reach there, though this water may be their cause.

This uncertainty as to the true sequence applies not only to the conditions regularly prevailing over one part of the sea or another, but even to sporadic

events that have often been invoked as evidence of the climatic effects of marine abnormalities; to the torrential rains, for instance, that accompanied the abnormal development of the warm 'El Nino' current along the coasts of Ecuador and of northern Peru early in 1925. Although most, if not all, students who have published accounts of this event have looked to the high temperature of the neighboring sea at the time as the cause of the exceptional rainfall that attended, it has been pointed out to us that no definite proof of this has yet been brought out. While the alteration of ocean currents in the regions was probably a contributing factor, both events may have been coincident results of a common cause — marked reduction in the strength of the trade winds.

Uncertainty of another sort as to which is cause, which effect, is illustrated in the North Atlantic, where recent and very searching investigations point to the direction of the wind as a cause of variations in the winter temperature of the surface of the sea, but where the winds in turn reflect the locations and intensities of the permanent or semipermanent centers of high and low atmospheric pressures, which may themselves be more or less affected by such changes in the sea temperature. In fact, alterations in the best known of these centers of atmospheric permanent high or low pressures, the 'Azores high'

and the 'Icelandic low' have been explained on this basis by some students. But here no general agreement has been reached, this being one of the cases (common in geophysics) where postulation has been much easier than demonstration.

The Northeast Pacific semi-permanent high is also known to shift north in summer, south in winter: and storms moving from the Aleutian region toward California sometimes linger over the Northeast Pacific for five to ten days, during which time it is only reasonable to suppose that their intensity is affected by evaporation from the water, and by the accompanying surface temperature. But very little is definitely known as to the less regular shifts in position of this or of other oceanic highs or lows, or to what extent (if at all) these shifts are caused by changes in sea temperatures.

Solution of the general relationship in this respect between sea and air is an essential preliminary to any attempt to establish whether or not oceanic variations are actually translated into weather abnormalities, except, perhaps, for localities where the climate is strictly oceanic (as on some islands), or where the wind constantly blows inward from the sea over the land.

To add to the difficulty that attends synthesis in this general field, alterations in the atmospheric centers may have climatic effects quite the opposite

of what the uninitiated might expect. Thus it has been pointed out that in the colder months unusually warm water off the southeastern United States may be expected to favor oceanic low pressure and cold weather, not warm, in the Eastern States. On the other side of the Atlantic, however, any intensification of the Icelandic low may be expected to bring warm weather along the land by strengthening the southerly component of the winds. Nor is the temperature the only element of climate affected by such alterations in the winds as may follow shifts in the highs and lows, for effects on the rainfall may equally be expected. Thus variations in the mean air temperature and rainfall for India may hark back, in part, to variations in the amount of ice melting from year to year in the Antarctic Sea. Variations in the rain that falls on the south-central part of the United States may in part reflect variations in the evaporation and in the air movement from the Caribbean Sea and Gulf of Mexico; while evidence so far obtained suggests that the dampness and temperature of winds blowing in from the sea (consequently the temperature of the ocean surface for a considerable distance up wind) has a part in governing the rainfall of Southern California.

Sir Napier Shaw, in his book 'Forecasting Weather' (1923, page 160), has recently remarked that actual analysis of North Atlantic weather 'has

been destructive of any hope of simple rules of weather sequence or for the movement of high and low pressure areas. The atmosphere over the North Atlantic is shown to be throughout the year in a state of turmoil which defies simplicity of description, and it is clear that something more than a process of classification is required before the sequences will become amenable to formulated law.' This statement by one of the most eminent of living meteorologists sufficiently emphasizes the difficulty with which any institution — far more any individual — is faced who undertakes serious investigation of the rôle that sea temperatures may play in the weather complex.

Although surface temperatures almost past counting have been collected in the past, it has been appreciated for many years that one of the difficulties of such investigation lies in the need for gathering reliable observations at shorter intervals, for various parts of the ocean, for only by such data would it be possible to follow, in detail, just what changes do occur in the sea.

It is pertinent here to consider how far the machinery that would be necessary for analytical investigation in this field now exists. So far as physical equipment goes, the answer would be encouraging for the North Atlantic, where steamers run regularly on so many routes that a close net of continuous oceanographic data could be obtained easily, if

thermographs, barographs, and so forth, could be installed on a sufficient number of ships, and if arrangements could be made for the ships' officers to give these instruments the needed attention; also to care for the records. In fact, continuous sea water thermographs have already been installed on steamers running in various parts of the world under the auspices of several different institutions, with highly instructive results. The hydrographic services also receive a continuous stream of observations from a variety of sources, and the weather bureaus are now developing a scheme of coördinated investigation as noted on page 239. In the other oceans data are much needed from regions that lie outside the regular steamship tracks, hence cannot be obtained without special arrangement.

The most serious obstacle to the advance of knowledge as to the general relationship between sea temperatures on one hand, and atmospheric temperatures and pressures on the other, has not been any intrinsic difficulty in obtaining the marine observations, but the inability of any existing agency to undertake analysis of the enormous mass of data that has already been amassed, and that will continue to accumulate at an appalling rate if continuous observations are taken on many ships running along many different routes. For such investigation to be of any practical value whatever, this analysis is

essential. It is also necessary to face not only the volume of work entailed, but also its extreme complexity, while it is obvious that efforts to work up the great mass of ocean temperatures already accumulated at several places would be an essential item in any broad-scale research in this general field. And all institutions so doing, whether governmental or private, should be encouraged to follow a common plan.

The magnitude of any such undertaking, if it were to be applied to any one of the ocean basins as a whole with the fringing lands, is quite beyond the capabilities of any private institution now existing or likely to be established. At present it is equally beyond the reach of any of the governmental weather services, for with meteorologists, as a body, unable to promise the legislatures that such analysis (even if continued for ten or twenty years) will produce commensurate economical results, it is not likely that governmental funds can be secured for large-scale investigations of this sort. Furthermore, there could be no attempt by governmental bureaus at official long-range weather forecasting based on sea temperatures (except perhaps for some locality especially favorable) until a rational basis for prediction be established by the proof that a correlation exists; until a sound method for translating such correlations into terms of weather be found; and until

arrangements be made for the regular collection of the necessary data. Even assuming these requirements to be met, official forecasts could hardly be given out until the methods had been tried out for a long term of years, because if such forecasts are to engender confidence, they must be verified by the event in a substantial majority of cases.

These difficulties unite to make this a field in which fertile results may be soonest expected from what is known as the 'case system' of investigation, while the extreme complexity of the basic problem makes it essential that the simplest cases be the first attacked, thus approaching as nearly as possible to the laboratory method. Furthermore, the impossibility (if we are to be intellectually honest) of promising immediate economic benefits therefrom, makes research institutions particularly appropriate centers for certain aspects of such work, in coöperation with the governmental weather bureaus.

The very encouraging progress that has been made in the experiment now being carried out by the Scripps Institution (just mentioned) corroborates this view, for it appears, at present, that temperature departures in the various parts of the Pacific are one of the classes of indicators that can be combined into cumulative forecasts of seasonal rainfall and perhaps of temperatures for Southern California at least, while recent investigations show a sequence of pressure

and temperatures across the Pacific Ocean, which suggests the effects of a transportation of heat by ocean currents. And while much work yet remains to be done to uncover the effect of other factors that are undoubtedly concerned, if the system is to be placed on an assured basis, even for this specially favorable locality, the suggestive results of the attempt, to date, not only justify the continuation of this line of work in Southern California, but point the need of investigations of the same sort in other representative regions chosen on the basis just stated (page 253). The relationship that rainfall in Ecuador and northern Peru bears to ocean temperatures off that coast offers a very promising case for study. Other vantage-points that seem favorable, because interpretation promises less difficulty there than in most parts of the world, appear to be the southwest coast of Africa, the northeastern Asiatic seaboard, northeastern Brazil, southern Alaska, and the Gulf and South Atlantic seaboards of the United States.

# CHAPTER VII

## PHYSICAL, CHEMICAL, GEOLOGIC, AND BIOLOGIC UNITY IN THE SEA

IN the preceding pages we have, for the sake of clarity, discussed certain of the underlying problems of oceanography as though the sea, in its physical and chemical nature, were a stable thing, controlling the activities of life within it, though hardly affected by the latter; and as though these problems could profitably be attacked independently one of another. But oceanographers, as a group, have come to realize, during the past quarter-century, that this is far from the truth; and with this realization the science of the sea has entered a new intellectual phase.

The foundation for this alteration in viewpoint, from the descriptive to the explanatory, was a growing realization (this could have come only after multitudes of facts had been accumulated) that in the further development of sea science the keynote must be physical, chemical, and biological unity, not diversity, for everything that takes place in the sea within the realm of any one of these artificially divorced sciences impinges upon all the rest of them. In a word, until new vistas develop, our ventures in oceanography will be the most profitable if we regard the sea as dynamic, not as something static, and

if we focus our attention on the cycle of life and energy there as a whole, instead of confining our individual outlook to one or another restricted phase, whether it be biologic, physical, chemical, or geologic. Examples of this fundamental unity face the oceanographer at every turn, for while the nature of the sea water governs the lives of the animals and plants that inhabit it, at the same time the functions of the latter are as constantly altering the nature of their environment in a way to which we see nothing comparable on land.

Perhaps the most obvious example of this (one already mentioned) is the constant draft that so many animals and plants make on the water for the materials with which they build their skeletons, as a result of which vast quantities of lime and of silica are constantly being withdrawn. And while some of this goes back into solution when the organisms die, other vast quantities accumulate on the sea floor, in deposits of lime compounds, and of silicates.

On the whole, by this process, lime is accumulating toward the equator, and around the coastlines, silica toward the poles and in the ocean deeps. Why is it that lime accumulates more rapidly on the bottom in shoal water than in deep? Is the solvent power of deep water the greater, as has often been supposed, or have we to do with some bacterial action?

The mass production of plants in the sea withdraws temporarily from circulation the nutrients they need, and there is a certain permanent loss after their death, as of nitrates decomposing to the gaseous state, and of phosphates going into chemical union with bottom sediments. Just how are these losses made up so that the balance is on the whole maintained? How far is the pulse in the available supply of these nutrient substances in the sea responsible for the sudden outbursts of unicellular plants in such unbelievable numbers that they are the most spectacular events in marine economy, and is it their exhaustion of the water that destroys them, or are they self limited in some other mysterious way? In like manner, while the degree of alkalinity of the sea, like that of our own blood serum, is constant within narrow limits and any wide variation means death, the great drafts of carbon that plants make in their photosynthetic activities, added to various other biologic and chemical happenings, are as constantly tending to alter the ionic concentration of the various electrolytes in the solution, and thereby to raise or to lower the alkalinity. But while alterations so caused may actually progress to the fatal limit in enclosed pools, this never happens in the open sea. What rôle in maintaining this fundamental balance, against their own tendency to upset it, is played by living creatures, and how do they

affect the cognate matter of the $CO_2$ tension of the sea water relative to that of the air?

These illustrations, with those given in the preceding pages, are perhaps enough to show that, at bottom, the composition of the sea water is as much a biologic as a chemical problem, even though in many cases its solution can come only *via* the discipline of chemistry. On the other hand, as is stated repeatedly in the preceding pages, most of the basic problems of oceanic biology equally focus around the fact that the oceans are filled, not merely with water, but with water that is 'salt.'

We can quote no better example of the intimacy with which the disciplines of the biologist, of the geochemist, and of the geophysicist unite in concrete cases, than is afforded by the broad problem of the means by which the uniformity of sea water is maintained, for it is obvious that some of the processes that are constantly tending to disturb the balance fall in one, some in another scientific subdivision.

Thus the problems that center around the fact that the solutes contributed with river water are very different in their composition from sea salts; the withdrawals by animals and plants in the formation of their shells; around the withdrawals of foodstuffs by plants, balanced against the contributions to the water of other stuffs as carcasses decay; or around the alterations in ionic dissociation that result

from additions and withdrawals, are biochemical. But, the diluting effect of the rain that falls upon the surface of the sea or of the fresh water that is poured in by rivers, and the concentrating effect of evaporation, all offer problems in physics. Only in conjunction, therefore, can chemist, geologist, and biologist hope to learn how the sea water remains so constant that we must analyze to parts per million, even to parts per thousand million, before we can express the existing variations in the relative proportions of its different salts; or how it is that the alkalinity of the sea never varies outside the narrow range in which protoplasm can live — is in fact as delicately balanced as the alkalinity of our own blood serum.

Another obvious line of connection between the biological and the physical-chemical realms in the sea is *via* temperature; no creature can live, much less thrive, if the water be too hot or too cold. But even as seemingly simple a constant as temperature cannot be considered *per se*, or as an adjunct, in the sea, because water has no inherent temperature of its own, but is given the latter by a complex of constantly changing factors such as solar radiation, back-radiation to the air, evaporation, and the melting of ice. Consequently, in our examination of temperature, we are led without a break into the fields of astrophysics, of meteorology, and of polar geography. We are also led, and very abruptly, to a

consideration of the circulation of the sea, because the temperature there at any given time and locality is largely controlled by the currents, as the latter transfer cool or warm water masses from place to place. There is, too, a direct mechanical connection between ocean circulation and the lives of the marine inhabitants quite as important as that *via* temperature, for currents also carry plants and animals about, likewise other materials of all sorts. Currents, in fact, play much the same rôle in marine economy as do railroads, or any other transportation system on land.

We must realize that, wonderful medium though sea water be for the support of life, any animal or plant would soon exhaust the vital possibilities of the water in its immediate vicinity unless some transportation system were in operation, either to carry the creature elsewhere (whether voluntarily by its own activity, or involuntarily) or to bring to it new water holding in solution or in suspension the substances that the organism in question needs. For the latter sort of transport, the currents and drifts of the sea are wholly responsible; largely so also for the former, by effecting the involuntary migrations of creatures young and old, a kind of dispersal that is constantly going on, and on a scale much broader than is generally appreciated. If the life of the eel is perhaps the most spectacular instance of this type of

migration that has yet been followed through to its conclusion, thousands of other kinds of sea animals and plants equally owe their geographic distribution (presence here and absence there), and their dispersal from the regions where they were produced to other regions where they pass the greater part of their lives, directly and solely to mechanical transport by ocean currents. This category of travelers includes the majority of our important food fishes, for most of these, when young, drift at the mercy of tide and current for considerable periods.

Circulation is also solely responsible, for example, for the aeration of the deeps, without which all but the uppermost stratum would be a waste more desert than the Sahara. Currents, too, largely control the distribution of salinity over the oceans; they wear down some coastlines and build up others; they distribute sediments over the bottom of the sea; and they so largely determine the climates of the continents and the system of winds that there is no possible way to disentangle oceanography from climatology.

Reasons as cogent as these make even the biologist admit, no matter how strictly he may confine himself to his own narrow niche, that the currents of the sea offer today one of the most intriguing fields of study in sea science. And, as let us repeat, this is true not only from the descriptive side (for we still

have much to learn even about the characteristics of the larger and more impressive ocean currents as described above — Gulf Stream, for instance — let alone the obscure) but from the standpoint of the physical forces that keep the circulation of the sea in its closed and continuous operation. So the unfortunate biologist, even if mathematics are to him a closed book, as is the case with too many of us, must perforce take as keen an interest as do his physical confrères, in the modern applications of mathematics to oceanic dynamics, and hold as high an appreciation of them.

Studies in whatever division of oceanography also lead inevitably into the province of the geologist, if they proceed far enough, for in last analysis the shapes, often the structures of the basins that hold the oceans, must always be taken into account.

The contours of the coastlines and of the submarine slopes confront the student at every turn, no matter what his chosen field of research, because these are the factors that control the whole system of submarine circulation, however the latter be kept in motion. And as every oceanographer realizes but too well, circulation is, in the end, the lifeblood of all events that take place in the sea.

The problems of sedimentation in the ocean also bridge the gap between chemist, biologist, and geologist, because the oozes that accumulate on the

floors of the deep basins so largely consist of the skeletons of animals and plants that sift down after death from the upper layers. Where, and in what numbers these skeletons commence to sink, is a problem as strictly biologic as any, for it depends in part on the geographic distribution of the species concerned, equally on their birth- and death-rate. But whether and in what quantities these skeletons do actually reach the bottom, also their effect upon the ocean water as they go back into solution (for given time enough, anything will dissolve in sea water) is a physical-chemical question. The ultimate fate of such of these skeletons as actually reach and accumulate on the bottom is a geologic question of the first rank, for reasons given in an earlier chapter. And the problems that center around the contributions that are made to the sea floor by reef-builders, and by other bottom-living animals, bridge the gap, no less directly, between the disciplines of biology and chemistry on the one hand, or geology on the other.

There is, we think, no need of further argument to prove that these several disciplines do inevitably interlock, or to point the intellectual necessity not only of recognizing, but of acting upon this unity, if we hope ever to gain any sound understanding of the sea, or of the lives of its inhabitants.

THE END